STUDIES ON TWO-PHASE FLOW AND BOILING HEAT TRANSFER IN INCLINED TUBES

WITH REFERENCE TO SOLAR SYSTEMS

By

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DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
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STUDIES ON TWO-PHASE FLOW AND BOILING HEAT TRANSFER IN INCLINED TUBES

WITH REFERENCE TO SOLAR SYSTEMS

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

By

MADDI MURALI KRISHNA

to the

DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
JANUARY, 1985

To My

PARENTS

- With LOVE

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CERTIFICATE

This is to certify that the work presented in this thesis entitled, "STUDIES ON TWO-PHASE FLOW AND BOILING HEAT TRANSFER IN INCLINED TUBES WITH REFERENCE TO SOLAR SYSTEMS" has been carried out by Mr. MADDI MURALI KRISHNA under my supervision and the same has not been submitted elsewhere for a degree.

Dated: January 24, 1985

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NOMENCLATURE

A	heat transfer area
Bo	boiling number
Co	convective number
C_1, C_2	constants defined by Equation 4.6A
C_3, C_4	constants defined by Equation 4.6B
c_{p_f}	specific heat of liquid phase
D	inside diameter of the tube
F	Reynolds number factor, $\left(\frac{Re_{TP}}{Re_f}\right)^{0.8}$
Fr	Froude number
f	friction factor
$\bar{f}$	friction factor evaluated using Duckler definition of two-phase viscosity
f_{TP}	two-phase friction factor
f_f	friction factor based on liquid alone flow
G	mass velocity
g_c	gravitational constant
h_C	two-phase flow convective heat transfer coefficient
h_L	single-phase convective heat transfer coefficient
h_N	nucleate boiling heat transfer coefficient
h_{TP}	two-phase heat transfer coefficient
h_f	heat transfer coefficient for liquid alone flow

h_{fg}	latent heat of vaporization
k	thermal conductivity
L	effective length of the test-section
m, n	exponents given in Equation 2.6
Pr	Prandtl number
p	static pressure
p_s	saturation pressure
Q	total heat flux
Q_C	forced convection heat flux
Q_B	fully developed boiling heat flux
q	rate of heat input to the test-section
Re	Reynolds number
R_f	liquid holdup
r, r_1	inside radius of the tube
S	supression factor, $(\Delta T_{se} / \Delta T_s)^{0.99}$
T_W	wall (inner surface) temperature
T_{Wav}	average of the inner surface temperatures (average of the temperatures at four locations on the circumference of the tube)
T_{Wm}	measured wall temperature
T_b	liquid temperature obtained by linear interpolation of the inlet and the outlet liquid temperatures of the test-section

T_s	saturation temperature
t	distance of the thermocouple junction from the inside surface of the tube
u	local velocity
u_m	velocity at axial location
V_T	total velocity
V_{sf}	superficial velocity of liquid
V_{sg}	superficial velocity of vapor
v	specific volume
v_{fg}	difference in specific volumes of saturated liquid and vapor
We	Weber number
X	Lockhart-Martinelli parameter for two-phase flow
x	mass vapor quality
x_i	mass vapor quality at the inlet of pre-evaporator E3
x_o	mass vapor quality at the outlet of pre-evaporator E3
y	distance from the tube wall
z	axial co-ordinate

Greek Letters

α	void fraction
$\bar{\alpha}$	mean void fraction
α_m	void fraction at axial location

β	volumetric quality
ρ	density
μ	viscosity
φ_f^2	two-phase frictional multiplier based on pressure gradient for liquid alone flow
φ_g^2	two-phase frictional multiplier based on pressure gradient for vapor alone flow
$\varphi_{fo,G}^2$	two-phase frictional multiplier based on pressure gradient for total flow assumed liquid at mass velocity, G
σ	surface tension
Θ	angle of inclination to horizontal plane
Ω	mass velocity correction factor in Baroczy correlation
$\left(\frac{dp}{dz}\right)$	total pressure gradient
$\left(\frac{dp}{dz}\,A\right)$	pressure gradient due to acceleration
$\left(\frac{dp}{dz}\,F\right)$	pressure gradient due to friction
$\left(\frac{dp}{dz}\,F\right)_f$	frictional pressure gradient assuming liquid alone flow
$\left(\frac{dp}{dz}\,F\right)_g$	frictional pressure gradient assuming gas alone flow
$\left(\frac{dp}{dz}\,G\right)$	pressure gradient due to gravitation
ΔT_s	wall superheat, $(T_w - T_s)$
ΔT_{se}	effective wall superheat

$\Delta T_{s,ib}$	wall superheat at the incipience of boiling
Δp	total pressure drop
ΔpA	accelerational pressure drop
ΔpF	frictional pressure drop
$(\Delta pF)_{fo}$	frictional pressure drop for total flow assumed liquid
ΔpG	gravitational pressure drop

Subscripts

TP	two-phase
W	wall
f	liquid
g	vapor
s	saturation
tt	liquid turbulent-vapor turbulent

SYNOPSIS

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Recently there is an increasing interest in solar energy utilization. Flow boiling is encountered in solar systems such as water pumping, process-steam generation, power generation, refrigeration and air-conditioning. Solar collector arrays are generally kept inclined to maximise the interception of solar radiation. Hence for design and operation of these solar systems, an understanding of two-phase flow and convective boiling is required. While there are extensive studies of flow boiling in vertical and horizontal tubes, there are none in inclined tubes. The objective of the present study is to obtain experimental data on heat transfer coefficients and two-phase pressure drops in inclined flow boiling and propose design correlations.

A flow boiling test loop, consisting of three pre-evaporators and one test-section with an arrangement to tilt

it to any angle between 0° and 90° from the horizontal, was built. Experiments were carried out using water as the fluid at atmospheric pressure in the range of mass velocity, quality and heat flux that are encountered in solar thermal systems. The temperatures around the thick walled copper test section and its inlet and outlet bulk fluid temperatures, heat flux were monitored using the H.P. data acquisition system to determine the boiling heat transfer coefficients. The pressure drops across the pre-evaporators and the test-sections were measured using differential manometers employing condensers close to the pressure taps. The quality profile along the pre-evaporators and test-sections was determined from the pressure profile constructed from the measured pressure drops. The flow patterns of the mixture coming out from the test-section were observed.

It was found that in bubbly or intermittent flow the heat transfer coefficient passed through a minimum with increase in angle of inclination. In annular flow, it was found that the inclination has insignificant effect on heat transfer coefficient. The measured boiling heat transfer coefficients for the vertical case were compared with those estimated using the Chen (1966), Bjorge et al. (unpublished) and Dengler-Addoms (1956) correlations. The Chen correlation gave better representation of the vertical flow data than the others. The Chen correlation has been extended for inclined flow boiling. Considering that both S and F functions depend on the angle of inclination, the functions S and F were evaluated for 0°, 30.5°, 46°, 67.5° and 90°. These functions showed a systematic variation with the angle of inclination. The relations for S and F with the angle of inclination were proposed. The comparison of experimental data with those estimated from the extended Chen correlation showed that the average and mean deviations are 9.2% and 0.84% respectively.

For computing frictional pressure drop from the total pressure drop, void fraction is required. Literature review indicates there are no reliable void fraction correlations for flow boiling in inclined tubes. Hence the following indirect method was employed. The commonly used void fraction correlations for vertical flow were found to differ considerably from each other. Employing these correlations, frictional pressure drop was computed for the vertical flow boiling case and was compared with the Baroczy (1965) correlation. It is found that Dengler-Addoms (1956) correlation gave best results. For inclined flow boiling, the void fraction estimated from the Dengler-Addoms correlation was multiplied by the correction factor proposed by Beggs and Brill (1973) to account for the inclination effect. The frictional pressure

drops were computed and their qualitative trends were discussed. It was found that the Baroczy correlation is representing most of the data within ± 50% error bounds for all angles of inclination. The Lockhart-Martinelli method of correlation was also attempted. The frictional multipliers were correlated in terms of mass velocity, two-phase flow parameter and angle of inclination using the multiple exponent regression analysis. The data could be fitted with an average and mean deviation of 26.8% and -8% respectively.

The flow patterns observed during heat transfer runs were presented and compared with the transition lines suggested by Weisman and coworkers (1979,1981). Most of the data fell in the annular and intermittent zone. It was observed that the annular to intermittent transition is not significantly affected by the angle of inclination.

The proposed heat transfer and pressure drop correlations can be used for design of the solar collectors with phase-change. However, further work is needed to obtain flow-pattern specific correlations.

CHAPTER 1

INTRODUCTION

Two-phase flow and flow boiling are encountered in a variety of fields such as nuclear and thermal power generation, desalination, air-conditioning, refrigeration etc. A recent addition to these is the solar energy utilization. Flow boiling is encountered in solar water pumping (Sudhakar et al., 1980; Kwant et al., 1982), solar refrigeration (Excell and Kornsakoo, 1982; Ahmad, 1982); solar power generation (Lehna, 1983), and solar process steam generation (Feustel, 1981). In these devices it becomes necessary to keep the solar collectors at an inclination from the horizontal to maximize interception of solar radiation. To design and operate these systems, an understanding of two-phase flow and flow boiling in inclined channels is required. An understanding of this phenomena is also desired in crude oil and natural gas gathering systems as the pipes are inclined many a time.

In two-phase flow, vapor and liquid may distribute in a variety of patterns. With change of orientation of the tube, the distribution gets affected. Since heat and momentum transfer are known to depend on vapor-liquid distribution in the tube, the inclination can be an important design parameter.

While two-phase flow and flow boiling in the vertical and horizontal tubes have been widely studied, the inclined case received little attention. In the recent past a few studies were reported on two-phase flow in inclined pipes (Beggs and Brill 1973; Spedding and his co-workers, 1977, 1980, 1981; Barnea, 1980) but none on flow boiling. There are indications in the literature (Chen 1978) that inclined flow boiling could be different from either vertical or horizontal two-phase flow and flow boiling.

In the present work an experimental study of two-phase flow and flow boiling was carried out with a view to provide design data for solar energy devices. It is known that in flow boiling a variety of flow patterns are encountered. To gain better understanding it is desirable to study these for each of the flow patterns. However, such a study demands extensive effort. Since this being the first study in inclined flow boiling and keeping in mind the immediate objective of providing the correlations for the design of solar systems, the studies were planned to obtain correlations which are applicable over a wide range rather than for specific patterns.

A flow boiling test-loop was built, and the experiments were conducted using water as the fluid near atmospheric pressure at angles of inclination 0° to 90° (from the horizontal) in the range of heat flux and flow rates that are generally encountered in solar collectors.

A brief review of literature pertinent to two-phase flow and flow boiling has been presented in Chapter 2. Chapter 3 deals with the description of experimental setup and procedure. Results and discussion of two-phase pressure drop and boiling heat transfer are presented in Chapter 4. Conclusions are presented in Chapter 5. The raw data of pressure drop and heat transfer coefficients are presented in tabular form in Appendicies C and B respectively.

CHAPTER 2

LITERATURE REVIEW

The two-phase flow and boiling heat transfer literature is voluminous. There are several books dealing with various aspects of the subject such as Collier (1981), Hsu and Graham (1976), Butterworth and Hewitt (1977) to name a few. Since the present study is concerned with the saturated flow boiling of water in inclined tubes at atmospheric pressure, only a brief review of the flow boiling heat transfer and two-phase flow literature pertinent to the present study is presented. No attempt was made to present exhaustive review of all the literatur

2.1 HEAT TRANSFER

Dengler and Addoms (1956) were the first to show that there are two mechanisms of heat transfer in flow boiling; namely nucleate boiling and two-phase forced convective heat transfer. They measured local heat transfer coefficients covering bubbly to mist flow regimes. The ratio of two-phase heat transfer coefficient, h_{TP}, and convective liquid heat transfer coefficient, h_L, was correlated in terms of $(1/X_{tt})$; where X_{tt} is the Lockhart-Martinelli parameter.

Guerrieri and Talty (1956) measured h_{TP} in a natural circulation loop for various organic fluids. They have correlated h_{TP} in terms of $(1/X_{tt})$. Bennett et al. (1959) correlated their vertical flow boiling data of water in terms of $(1/X_{tt})$ and heat flux. Shrock and Grossman (1962) and Collier and Pulling (1962) correlated their data in terms of $(1/X_{tt})$ and boiling number, Bo.

From the incipience of boiling to annular flow there can be three zones in flow boiling. In the first zone nucleate boiling dominates and in the second zone both nucleate boiling and convective transfer are significant. Gradual suppression of nucleation in this zone leads to the third zone where only forced convective transfer prevails. Using Rohsenow's superposition principle (1952), many investigators arrived at different correlations of heat transfer in flow boiling.

Chen (1966) proposed the following correlation for vertical saturated flow boiling heat transfer,

$$h_{TP} = h_C + h_N \qquad 2.1$$

where h_{TP} is the local heat transfer coefficient, h_C is the contribution due to convection and h_N is contribution due to nucleate boiling. For convective transfer contribution, he adopted the Dittus-Boelter equation in which properties and Reynolds number, Re, associated with two-phase mixtures are employed. He showed that

$$h_C = 0.023 \, Re_f^{0.8} \, Pr_f^{0.4} \, \frac{k_f}{D} \, F \qquad 2.2$$

where F is a function of $1/X_{tt}$.

For nucleate boiling contribution, he modified the Foster-Zuber pool boiling correlation so as to account for the steep temperature gradient along the bubble height encountered in flow boiling by introducing a suppression factor, S. Thus for nucleate boiling contribution, h_N, he obtained

$$h_N = 0.00122 \quad \frac{k_f^{0.79}\ c_{pf}^{0.45}\ \rho_f^{0.49}\ g_c^{0.25}}{\sigma^{0.5}\ \mu_f^{0.29}\ h_{fg}^{0.24}\ \rho_g^{0.24}} \quad \Delta T_s^{0.24}\ \Delta P_s^{0.75}\ S \qquad 2.3$$

where

S = suppression factor $(\Delta T_{se}/\Delta T_s)^{0.99}$

k_f = thermal conductivity of liquid phase

c_{pf} = specific heat of liquid phase

ρ_f = density of liquid phase

g_c = gravitational constant

Δp_s = change in saturation pressure, determined from ΔT_s

σ = surface tension

μ_f = viscosity of liquid phase

h_{fg} = latent heat of vaporization

ρ_g = vapor density

ΔT_s = wall superheat $(T_W - T_s)$

ΔT_{se} = effective superheat with flow.

Both the functions F and S were determined from the data of water and organic fluids. This is one of the best available correlations (Kandlikar and Thakur, 1983; and Jallouk, 1974).

To account for the effect of Prandtl number, Pr, Bennett and Chen extended the Chen correlation using a modified Reynold's analogy for liquids with higher Pr_f.

Bjorge et al. (unpublished) extended the Rohsenow method of superposition for correlating the flow boiling heat transfer from subcooled to high quality range. For high quality region, where annular flow exists, they suggested the boiling heat flux, Q, can be found as

$$Q = Q_C + Q_B \left[1 - \left(\frac{\Delta T_{s,ib}}{\Delta T_s} \right)^3 \right] \qquad 2.4$$

where $\Delta T_{s,ib}$ is the wall superheat at the incipience of boiling The term multiplying Q_B is similar to Chen's S factor. They recommended the evaluation of Q_C from the Traviss et al. equation modified by Hall, Q_B from the Mikic-Rohsenow correlation, and $\Delta T_{s,ib}$ from the Bergles and Rohsenow relation. For the subcooled and low quality regions, they used the Bergles and Rohsenow superposition method.

$$Q = \left\{ Q_C^2 + Q_B^2 \left[1 - \left(\frac{\Delta T_{s,ib}}{\Delta T_s} \right)^3 \right]^2 \right\}^{1/2} \qquad 2.5$$

They recommended the evaluation of Q_C from the Colburn forced convection equation. Q_B from the Mikic-Rohsenow correlation and $\Delta T_{s,ib}$ from the relations developed by Bjorge. These equations are given in Table 4.1. On comparing these correlations with water data, they found that their correlation is slightly better than Chen's correlation.

Hughmark (1982) also employed the superposition of nucleate boiling and convective transfer contributions to obtain flow boiling heat transfer. He observed that the nucleate boiling contribution can be obtained from Chen's equation by setting $S = 0.25$. He proposed methods of calculating pressure drops and convective heat transfer for annular flow in the cases of vertical downward, vertical upward and horizontal flows. He tested the models with the experimental data covering wide range of physical properties.

Shah (1976) presented a graphical correlation in terms of h_{TP}/h_f versus convective number, Co, with boiling number, Bo, and Froude number, Fr, as parameters. In this correlation, he accounted only nucleate boiling in low quality region, only forced convective transfer in higher quality region and both in transition region. The correlation is applicable for both vertical and horizontal flow boiling. Considering both nucleate boiling and forced convective transfer over the entire range of quality, Kandlikar and Thakur (1983) obtained expressions for both vertical flow and horizontal flow in terms of parameters used by Shah (1976)

Steiner and Schlunder (1976) reported data for the horizontal saturated flow boiling and pressure drop of nitrogen. They observed that flow boiling correlations like that of Chen, Chawla etc. did not represent their data well. They ascribed this to the wettability and drainage effects. They correlated their data by extending Stephen's correlation to account for mass velocity and wettability. The effect of mass flow rate on heat flux in nucleate boiling region was explained in terms of bubble frequency and bubble diameter relations.

Stephen and Aurscher (1981) proposed a correlation for pool boiling based on large data of several substances using dimensional analysis. They modified the forced convective boiling correlations proposed by Rohsenow, Kutateladze and Chawla by replacing the nucleate boiling term with the proposed one. They found that the modified Chawla equation gave fairly accurate representation of the experimental data of water, hydrocarbons, cryogenic fluids and refrigerants.

There are no studies on the effect of angle of inclination on boiling heat transfer. However, Chen (1978) studied the influence of angle of plate heater on heat transfer coefficients and bubble frequencies in pool boiling of Freon-22. His results show that the heat transfer coefficient increased with angle from 0° to 150° (horizontal being 0°) and then decreased to a minimum value at 180°. He evaluated the parameters of the Rohsenow correlation for each of the angles studied and proposed relations for them in terms of Θ . This study indicates that the flow boiling heat transfer might depend on the angle of inclination. Lavin and Young (1965), who studied both vertical and horizontal flow boiling of Freon-11 and Freon-22, classified the flow regimes as nucleate boiling, annular, and mist flow. They found that the heat transfer coefficients are much higher for horizontal flow than vertical in the case of annular regime and the orientation did not make any difference in the other two regimes.

From the literature review it appears that no systematic study of inclined flow boiling has been done so far.

2.2 PRESSURE DROP

The pressure drop of two-phase flow, hereafter referred to as total pressure drop, ΔP, is generally considered to consist of three components, namely gravitational pressure drop, ΔP_G, accelerational pressure drop, ΔP_A, and frictional pressure drop, ΔP_F. The estimation of these components requires the knowledge of void fraction. A brief review of the relevant literature on void fraction is given below.

2.2.1 Void Fraction

Perhaps the only source of data available on void fraction in flow boiling at low pressure in the open literature is that of Dengler and Addoms (1956). They measured void fraction in the vertical upward flow boiling using a radioactive tracer technique and correlated their data by the Lockhart-Martinelli method. The range of parameters covered are: pressure from 51.7 to 275.8 kPa, mass velocity from 63 to 1514 kg/m^{2}s, quality from 0.0 to 70 %. Isbin et al. (1957) obtained void fraction data using the γ-ray absorption in the adiabatic steam-water flow under flashing conditions in a vertical tube of 0.022 m diameter at atmospheric pressure. The quality was varied from 0.0 to 4.0 %. The comparison of the data with that of Dengler and Addoms showed poor agreement.

Most of the void fraction data are of isothermal flow of the air-water or steam-water mixtures. There are several correlations of void fraction and some of these are based on the Bankoff (1960) variable density model. Bankoff assumed that the void fraction and velocity profile can be expressed by the power law relation i.e.

$$\frac{u}{u_m} = \left(\frac{y}{r}\right)^{\frac{1}{m}} \quad \text{and} \quad \frac{\alpha}{\alpha_m} = \left(\frac{y}{r}\right)^{\frac{1}{n}} \qquad 2.6$$

where u and α are the local velocity and void fraction, respectively. u_m and α_m are the values at axial location. y is the distance from the tube wall and r is the tube radius, and m and n are arbitrary exponents. He obtained

$$x = \left(1 - \frac{\rho_f}{\rho_g}\right) + \left(\frac{\rho_f}{\rho_g} \; \frac{K}{\bar{\alpha}}\right)^{-1} \qquad 2.7$$

where x is mass vapor quality. $\bar{\alpha}$ is mean void fraction and

$$K = \frac{2(m+n+mn)(m+n+2mn)}{(n+1)(2n+1)(m+1)(2m+1)}$$

Using the steam-water data he found that

$$K = 0.71 - 0.0001\,p$$

where p is in psia, for pressures upto 1000 psia. The Armand correlation (1946) gives the parameter K as

$$K = 0.833 + 0.05 \ln p$$

Later, Hughmark (1962) considered that void distribution (hence the parameter K) is affected by buoyancy, inertial, viscous and surface tension forces. Using the air-water and steam-water data of vertical flow in pipes of diameter from 0.016 to 0.064 m, he correlated K in terms of Re, Fr and We. Duckler (1964) made a comparison of several void fraction correlations using a large data bank and found that the Hughmark correlation gave the best agreement with the data. Gregory (1975) also made a comparative study of seven void fraction correlations using horizontal and near horizontal flow data. They recommended the use of Lockhart and Martinelli or Beggs and Brill correlation for low liquid holdup (≤ 0.25) and the Hughmark correlation for higher liquid holdup.

The void fraction in the inclined flow has received considerable interest in the recent past. Beggs and Brill (1973) measured liquid holdup of the air-water flow in pipes inclined from -90° to + 90° and observed that liquid holdup attained a maximum at about 50° and a minimum value around -50°. They divided the flow pattern as segregated, intermittent and distributed. For each of these flow patterns, they gave correlations for the ratio of holdup at an angle of θ to holdup at $\theta = 0°$ in terms of θ, volumetric quality, β, and Fr.

Nguyen and Spedding (1977) obtained an equation for holdup which is valid for all types of flows. They showed that the semi-theoretical relations available in literature can be deduced from their relation as special cases. In a companion pape they have reported experimental holdup data for air-water flow in a pipe inclined from +90° to -90° from the horizontal. They have divided the flow into three regimes and gave correlations applicable for individual angle of inclinations employing the theoretical expressions mentioned above. They observed that the agreement of their data with Beggs and Brill correlation was poor

Lin (1983) presented the holdup correlations for inclined flow that appeared in the Soviet and Chinese literature. These correlations were developed for the steam-water flow at high pressures.

2.2.2 Frictional Pressure Drop

The frictional pressure drop is known to depend on the flow pattern, heat flux and angle of inclination, besides the physical properties, quality, mass velocity and flow geometry.

Lockhart and Martinelli (1949), in a classic paper, obtained a method of correlating the frictional pressure drop in terms of the two-phase frictional multiplier, $\tilde{\phi}$.

$$\phi_f^2 = \left(\frac{dp}{dz}F\right) / \left(\frac{dp}{dz}F\right)_f$$

and
$$\phi_g^2 = \left(\frac{dp}{dz}F\right) / \left(\frac{dp}{dz}F\right)_g \qquad 2.8$$

and the two-phase flow parameter, X, given by

$$X = \left(\frac{dp}{dz}F\right)_f / \left(\frac{dp}{dz}F\right)_g \qquad 2.9$$

where ϕ_f^2 = two-phase frictional multiplier based on pressure gradient for liquid alone flow.

ϕ_g^2 = two-phase frictional multiplier based on pressure gradient for gas alone flow.

They have obtained the correlation based on the isothermal horizontal flow data. Later workers recognised that φ_f^2 also depends on mass velocity. Le Tourneau and Troy (1960) applied the mass velocity correction factors to the two-phase frictional multipliers. Baroczy (1965) defined the friction multipliers somewhat differently and gave a graphical correlation involving quality, mass velocity and property index. This correlation acclaimed to be one of the best among the available (Weisman & Choe 1978; Collier, 1981). Later Chisholm (1973), using Baroczy's correlation as basis, obtained analytical expressions for prediction of the frictional pressure drop which are convenient for use in flow boiling computations.

It has been observed that the frictional pressure drop in flow boiling is more than that in isothermal flow. Based on the steam-water data, Tarasova et al. (1965, 1966) proposed the following empirical correlation to account for the effect of heat flux:

$$\frac{(\Delta P)_{heated}}{(\Delta P)_{unheated}} = 1 + 4.4 \times 10^{-3} \left(\frac{q/A}{G}\right)^{0.7} \qquad 2.10$$

where $\frac{q}{A}$ = heat flux, W/m^2

G = mass velocity, kg/m^{2}s

Recently, Shoukri et al. (1981) reported that the application of constant heat flux results in higher pressure drop over adiabatic flow at all qualities in the case of horizontal flow. They found this effect to be dependent on pressure as well as mass velocity. Interestingly enough, they observed that the increase in frictional pressure drop due to heat flux passes through a peak as quality increases from 0.0 to 0.3.

Employing the Colebrook-White equation for the two-phase friction factor, the definitions of Re and f used in the homogeneous flow, Beattie and Whalley (1982) obtained simple but general expressions for two-phase frictional pressure drop. They compared the proposed as well as a number of other correlations with experimental data and showed the proposed one is as good as the alternative complex methods.

Apart from the above variables, the angle of inclination was also observed to have significant effect on the frictional pressure drop. The interest in the effect of inclination dates back to 1939. Boelter and Kepner (1939) reported the total pressure drop data for air-water and air-oil flow at an inclination of 9.5°. No correlation was reported. However, they noted that Re, Fr and We numbers are the correlating variables. Kosterin (1949) observed the change of flow patterns with inclination and noted that the effect was high at low liquid flow rates. He gave a correlation for the friction factor in terms of single phase friction factor, gas flow rate and Fr number. Baker (1957) and Brigham et al. (1957) also reported the total pressure drop for inclined pipe flow, but since liquid holdup data were not obtained no valid conclusions could be drawn from their work. Guzhov et al. (1967) presented a frictional pressure drop correlation in a form similar to that of Kosterin (1949). They have reported a holdup correlation. Ney (1968) and Fuentes (1968) reported the pressure drop and holdup data on upward inclined flow from 0° to 90°. However, the range of flow rates was very narrow.

Singh and Griffith (1970) developed a model for slug flow in inclined flow. Neglecting the pressure loss along gas slug and considering that the pressure drops depend only on shear of the liquid slugs at the wall, they obtained an equation for the frictional pressure drop:

$$\left(\frac{dp}{dz}\,F\right) = 2\, f_f\, \rho_f\, V_T^2\, R_f\, D^{-1} \tag{2.11}$$

Vermulen and Rayn (1971) proposed a model for the frictional pressure drop for the slug flow in horizontal and inclined pipes. They obtained an expression for the pressure drop in terms of friction factor, slug length (or slug frequency) and the holdup. They used the Lockhart-Martinelli correlation to estimate the liquid holdup. The slug length was found from the measured slug frequency. They compared the model with their pressure drop data obtained from experiments conducted using air-water flow in inclined tubes (-7° to + 7°) and found it to be in good agreement. Bonnecaze et al. (1971) modelled the slug flow for ± 10° inclinations and obtained expressions for the frictional pressure drop and liquid holdup. Based on the experimental data, they proposed correlations for friction factor in slug flow.

Beggs and Brill (1973) obtained the frictional pressure drop in inclined pipes of 2.54 cm and 3.81 cm diameter for air-water flow. The angle of inclination was varied from -90° to + 90° from the horizontal. The ratio $f_{TP}/\bar{f}$ was correlated in terms of liquid holdup and volumetric quality; f_{TP} is the observed homogeneous friction factor and $\bar{f}$ is evaluated using the Dukler definition of two-phase viscosity. It may be recalled that they have also presented a general holdup correlation for inclined flow.

Spedding et al. (1982) have reported extensive frictional pressure drop data for the air-water flow at atmospheric pressure in inclined pipe of 4.55 cm diameter at angles ranging from - 90° to + 90° from horizontal. The data were presented as plots of frictional velocity (based on liquid properties) versus total velocity for each angle of inclination with the superficial velocity as a parameter. Even though the way data were presented is not convenient to use, the qualitative trends were shown effectively. They have highlighted a number of operational and design criteria for the inclined two-phase flow systems.

The above few studies on two phase flow in inclined tubes indicate that the frictional pressure drop depends on the angle of inclination. However, no study has been reported for flow boiling.

CHAPTER 3

EXPERIMENTAL DETAILS

This chapter presents details of the experimental set-up, experimental procedure and results of some of the performance tests.

3.1 EXPERIMENTAL SET-UP

A schematic diagram of the flow boiling loop is shown in Figure 3.1. It consisted of a feed tank (A), circulating pumps (C and D), rotameter (F), preheating tank (PH), test-section assembly, vapour-liquid separator (J) and condenser (K). The test-section assembly was composed of three pre-evaporators (E1, E2 and E3), two test sections (T1 and T2) and a glass section (I). The description of these units is given below.

Figure 3.2 shows the details of the test-section. The test-section was made out of a 38 mm diameter copper rod. A bore was drilled in the copper rod and reamed to get an inner diameter of 12.7 mm. The surface roughness was measured with a profilometer and was found to be 0.62 microns. To fix the teflon gaskets a step 8 mm deep and 25 mm in diameter was made on both ends of the test-section as shown in Figure 3.2. The total length of test-section was 82 mm and its effective heating length was 66 mm.

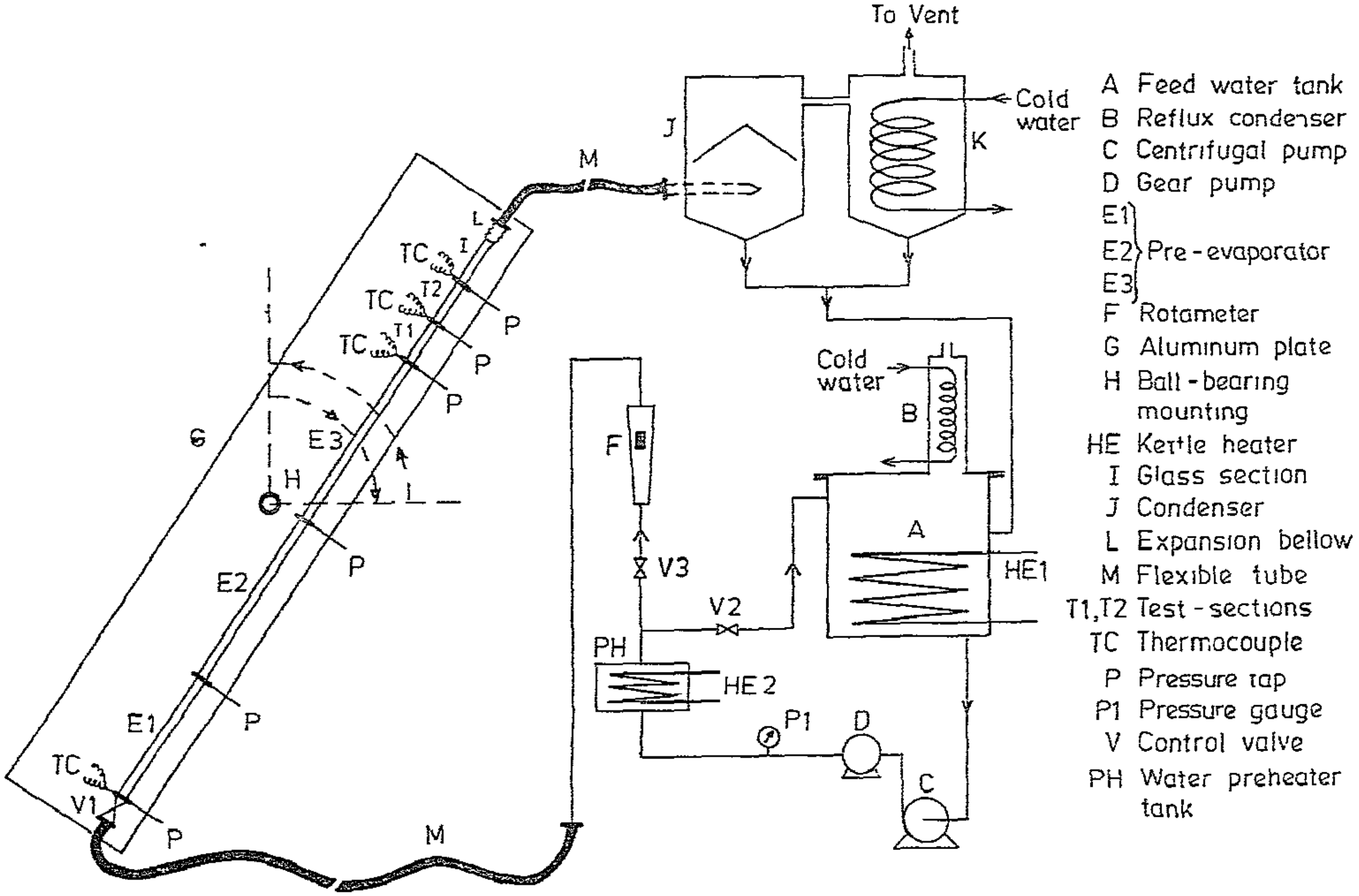
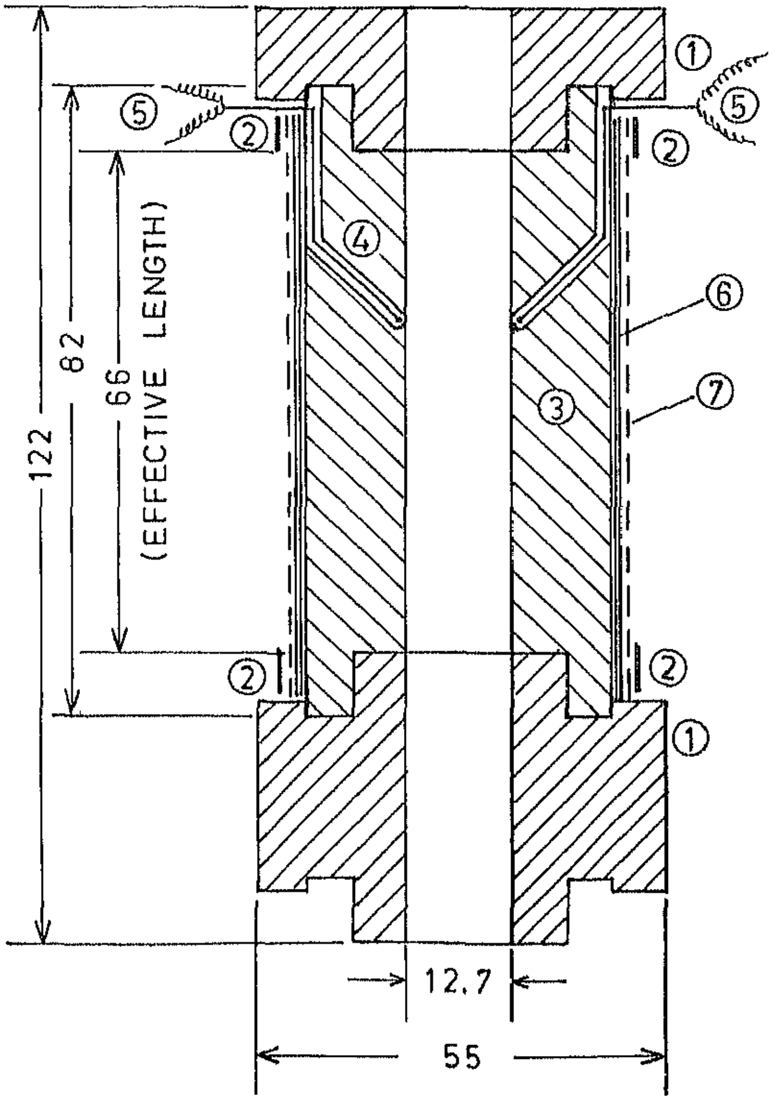


Fig 3.1 Schematic diagram of the flow boiling loop



1 Teflon Gaskets
2 Clamps
3. Copper test-section
4 Inclined hole for thermocouple
5. Thermocouple
6 Glass-Fibre cloth
7 Heating element

(All dimensions in mm)

Fig. 3.2 Test-section with teflon gaskets.

Four holes of 1 mm diameter at an inclination of 45° to the axis and about 15 mm long were drilled in the wall in such a way that the blind end of the hole is 1 mm from the inner surface. Grooves of 1 mm width and 1.5 mm depth were made on the outer wall from the holes to the end of the test-section. Teflon-insulated thermocouples were inserted into the holes just after filling the holes and grooves with conducting silver paint (Sunshine Scientific Instruments, USA). These were taken to the end of test section through the grooves. Thermocouples were held in position by applying a thin layer of Araldite (epoxy resin) on the bottom of the groove. The outer surface of the test-section was covered with a layer of glass fibre cloth. A nichrome strip (7.5 Ohm/m) 3 mm wide was wound over the effective length of the test-section and then clamped using copper strips. The heater winding was so positioned that it was directly above the inner boiling surface as shown in Figure 3.2. The winding of the nichrome strip on the test-section was done on a lathe to get uniform spacing and tension. Teflon gaskets were inserted into the grooves at the either end of the test-section as shown in Figure 3.2. The shape and thickness of teflon gaskets ensured uniform heat flux distribution throughout the effective length of the test-section by preventing heat conduction through the unheated section. Thermocouples were inserted in the teflon gaskets to measure temperature of two-phase mixture at the inlet and outlet of the test-sections (thermocouple junctions were placed close to the axis of the tube). The power supply was given to the heaters from Automatic Voltage stabilizer (1581-A, General Radio, USA). The test-section was insulated by 60 mm thick glass wool followed by asbestos tape.

The pre-evaporators E1, E2, E3, were made of copper tubes of 12.7 mm ID and 1.6 mm thick, and of lengths 281, 311 and 325 mm, respectively. The details of E3 are given in Figure 3.3.

The flange of pre-evaporator tubes also served as pressure taps. Each of the pressure taps consisted of an annular chamber (formed by a groove in the flange and the copper tube as shown in Figure 3.3) connected with the inside of the tube by four holes. The holes are 1 mm in diameter. The pressure taps were connected to small glass condensers, which in turn were connected to differential manometers. The heating elements of the pre-evaporators were wound in the same manner as that of test-section heater winding. The power ratings of pre-evaporators E1, E2 and E3 were 1.5, 1.0 and 1.2 kW, respectively. These were isolated from each other by using 10 mm thick teflon gaskets. The temperature of the inlet liquid at E1 was measured by a thermocouple inserted in the flange. All the heater voltages were regulated by using auto-transformers. The required mass vapor

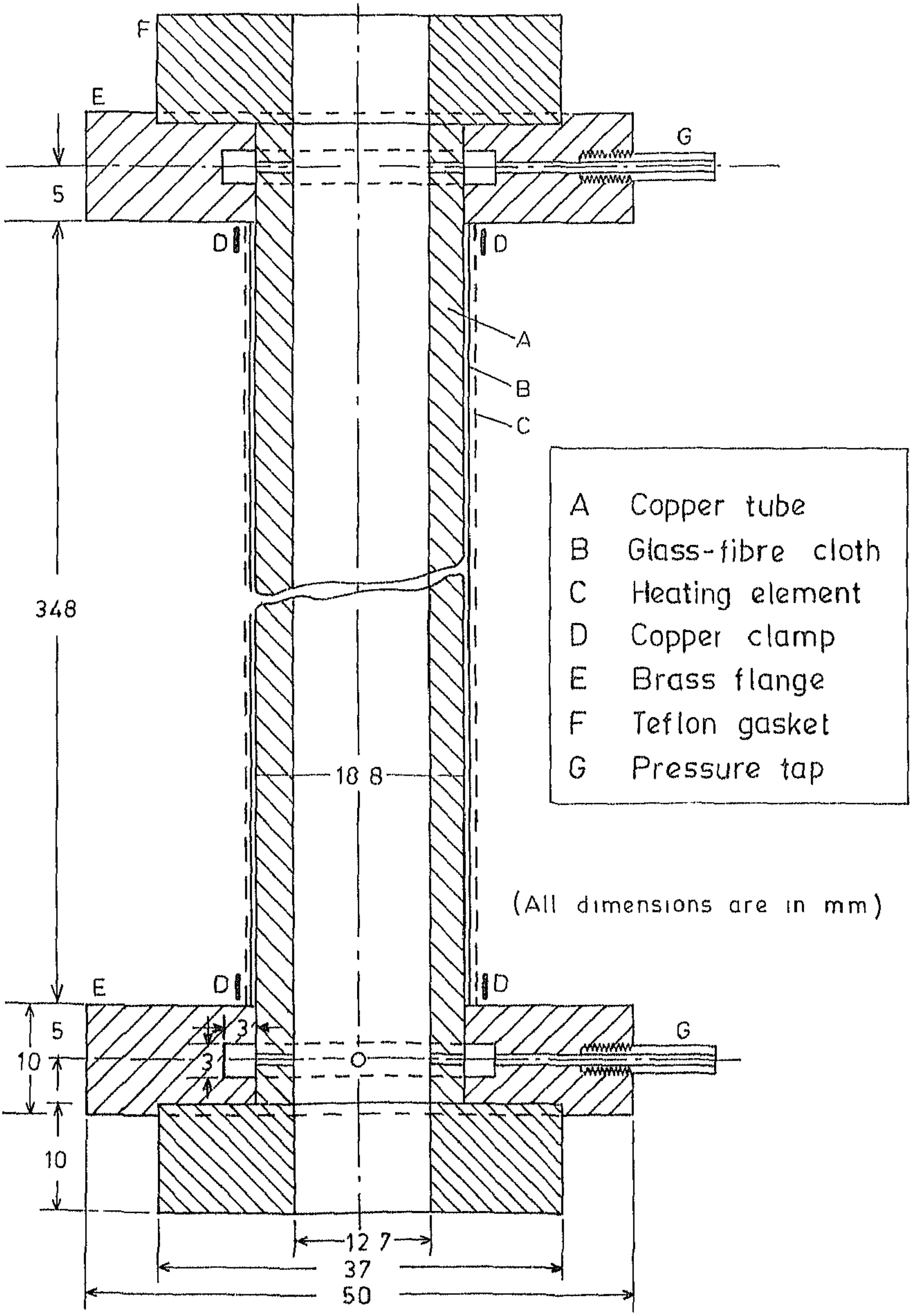


Fig 3.3 Cross-sectional drawing of pre-evaporator (E3) assembly.

quality at the test-section inlet was obtained by adjusting heat inputs to the pre-evaporators.

To observe the vapor-liquid flow patterns, a glass section was incorporated at the exit of T2. The glass section consisted of a 12.7 mm ID and 0.16 m long pyrex glass tube with Kovar metal joints at both the ends. Flanges were fitted to either end of Kovar tubes. A brass bellow was fixed at one end of the glass section to protect it from breakage due to thermal and mechanical shocks.

All the pre-evaporators were insulated by 50 mm thick glass wool and then by asbestos tape. Care was exercised during the fabrication to ensure the formation of hydraulically smooth tube. The test-section assembly was fixed rigidly to an aluminum plate of 0.35 m x 2 m x 6 mm, which in turn was mounted on a slotted iron angle structure with a ball bearing arrangement at the centre of the plate. By this arrangement the test-section assembly could be oriented to any desired inclination.

A brass feed tank (A) of 0.4 m dia.and 0.3 m height, fitted with two kettle heaters of 1.5 kW each,was used to heat the feed water to its boiling point. A reflux condenser (B) was fitted on the top of the feed tank as shown in Figure 3.1. Two pumps, a centrifugal pump and a gear pump connected in series, were employed to circulate water in the test-loop. It was observed that the use of a single pump gave rise to flow oscillations at low flow rates due to insufficient head developed. These pumps could generate a pressure of 400 kPa at the outlet which was then dropped across the valves V1 and V2, so that the flow rate does not respond to the small changes in the pressure drop across the test-section assembly. Another feed pre-heater tank (PH) was provided at the exit of the gear pump to ensure the water is at saturation temperature at the inlet of test-section assembly. The preheater was a brass tank of 0.14 m dia and length 0.12 m provided with a kettle heater whose heat input was controlled using a auto-transformer. A rotameter (Schutte and Koerting Co., USA) was used to measure the water flow rates in the test section assembly. It has a sensitivity of 9 cc/min/div.

The exit of test section assembly was connected to a separator and condenser assembly. The separator (J) and condenser (K) were brass tanks of 0.25 m ID x 0.3 m height and 0.15 m ID x 0.2 m height, respectively, with conical bottoms. The inlet port of the separator was fitted in such a way that two-phase mixture enters the separator tangentially. The condenser was provided with a copper coil of 3 mm ID and with a heat transfer area of 0.05 m^2. The liquid outlets of the condenser and separator were connected to the feed water tank to recycle the water by gravity.

The feed tank, rotameter, separator and condenser were all fixed on another slotted angle structure that was fitted with wheels. The separator and the condenser could be positioned at any desired height in accordance with the orientation of the test-section assembly. Brass pipes of 25 mm diameter were used to interconnect various units. In order to avoid vibrations being transmitted from one structure to another, the interconnecting pipe lines between the two structures were made using flexible tubes (Pure gum vacuum tubing, Goodyear Rubber Products, USA).

To test suitability of the rubber tube, a small portion of the tube was kept in boiling water for 10 hours. It was noticed that the tube was unaffected by boiling water and the water was observed to be as clear as before use. However, the rubber tube was kept to minimum lengths by employing brass tubes wherever possible. Further, during experimentation, the water was changed every day to avoid accumulation of possible contaminants due to long exposure and the test-section was cleaned frequently. No deposition was seen at any time.

3.2 MEASUREMENTS

3.2.1 Temperature Measurements

Teflon-insulated copper-constantan thermocouples (TT-T 30, 30 gage, Omega Engineering, Inc., USA) were used to measure temperatures. Reference junctions of the thermocouples were insulated by a thin coating of araldite epoxy and all the junctions were tied together and kept in a flask containing water at room temperature. The temperature of the water was measured by a calibrated mercury thermometer of 0.1°C accuracy. From each thermocouple, a pair of copper wires was taken to the Data Acquisition system through a thick aluminum conduit (to minimize noise pickup).

The e.m.f. of thermocouples was monitored using a Hewlett-Packard Automatic Data Acquisition system (HP 3052A). It consisted of 3455A Digital Voltmeter (DVM), 3495A scanner and a 9825A programmable calculator. The DVM is a 6-1/2 digit integrating voltmeter capable of measuring DC, RMS, AC and resistance. It has one microvolt sensitivity and 120 dB ECMR with the scanner DC measurement speeds upto 19 channels/sec. The DVM has a high resolution mode under which measurement resolution was 1 part/1.5 million. The DVM was set in this mode while monitoring thermocouple e.m.fs. The e.m.fs. of all the thermocouples were converted to temperatures using the temperature subroutine that was supplied by the company as a software package. The subroutine has the NBS table accuracy.

To have a check on the noise pickup, a pair of copper wires which were joined at the setup was taken alongwith the other wires, and connected to a channel of the scanner. This channel was also scanned alongwith the other channels and the measured voltage due to noise pickup was converted to temperature in all the runs. The noise pickup was always observed to be within ± 0.03°C. When the test section heater was 'ON', the thermocouples, which were fixed to the wall appeared to pickup some periodic noise depending on the applied voltage across test section heater. It was observed that the problem can be overcome by averaging several readings, obtained from a single thermocouple. From a thermocouple, a set of twenty readings at 5 readings/sec was taken and an average of these was taken to be the temperature. The average values of different sets at a steady state were found to be within ± 0.05°C.

3.2.2 Pressure Measurements

Pressure drop across the different sections (see Figure 3.1) was measured by differential manometers using carbon tetrachloride as manometric fluid. Absolute pressure at the inlet of E1 was measured by a mercury manometer. These measurements enabled determination of saturation pressure and temperatures at various points of the test-section assembly.

3.2.3 Current and Voltage Measurements

The current in the test-section heater was measured by calibrated multimeter (Motwane). In order to measure current in the pre-evaporators standard resistors were connected in series with the heaters. The voltage drop across standard resistors and heaters were monitored using the data acquisition system.

3.2.4 Accuracy of Measurements

Measurement accuracy of various instruments and maximum possible error due to fluctuations of the reading are reported in Table 3.1. The above limits of accuracy can lead to maximum possible overall error of ± 3.5 % in heat transfer coefficient and ± 3 % in mass vapour quality.

TABLE 3.1

INSTRUMENTAL ACCURACIES AND ERROR BOUNDS

Measured variable	Meter Accuracy	Expected Maximum Errors due to Fluctuations
Test-section voltage	+ 0.6% of the reading	± 0.20V in 100V
Pre-evaporator voltage	+ 0.6% of the reading	± 2 V in 220V
Test-section and pre-heater currents	± 0.025A	-
Differential pressure	± 6 Pa	± 0.1% of the reading when G=380 to 750 kg/m^2s ± 3% of the reading when G=125-250 kg/m^2s
Absolute pressure	± 70 Pa	± 70 Pa
Temperature:		
wall	± 0.015 °C	± 0.05 °C
liquid	± 0.015 °C	± 0.03 °C
Mass velocity	± 0.7 kg/m^2s	± 2.4 kg/m^2s

3.3 EXPERIMENTAL PROCEDURE

The feed tank (A) was filled with distilled and deionised water and heated to its boiling temperature (the vapor evolved in the feed tank was condensed using the reflux condenser). The pumps were switched 'on' keeping valves V1 and V2 closed with bypass valve V3 opened. Then V1 was opened fully and the flow of water was diverted to the test loop by gradually opening the valve V2 and closing the valve V3 fully. Next, the flow rate was adjusted to a preselected value by carefully adjusting the valves V1 and V2. Most of the pressure head was allowed to drop across valve V2. The valve V1 was closed to such an extent that the periodic flow oscillations were prevented. Then all pre-evaporator heaters and test section heaters were brought to their full heating capacity. After the system was stabilized (usually it took about one hour to stabilize), then all heaters were adjusted to preselected values. The temperature of water entering the test section assembly was adjusted by varying the heat input to preheater (PH) such that it was almost at saturation temperature (slight subcooling $\leq$ 0.2 °C was maintained to ensure zero quality). When the wall temperatures, bulk liquid temperatures and the rotameter reading were steady for more than ten minutes, the data collection was monitored by running a stored program on the computer. While the automatic data acquisition was being done, various other data such as the readings of manometer, rotameter and reference junction temperature, and current to the test-section heater were recorded and later on fed to the computer through the key board. Soon after, following quantities were computed:

(a) Temperatures and currents,

(b) Heat flux,

(c) Mass velocity,

(d) Pressure drop and pressure gradient across various sections

(e) Quality and saturation temperature at various locations (15 locations),

(f) Pressure drop analysis consisting of void fraction, the components of pressure drop due to gravitation, acceleration and friction across E3.

The entire procedure described above constituted one run. Keeping the other parameters constant, the heat flux was decreased in steps from highest to the lowest value. This was done to ensure all possible active sites on the surface are activated.

3.4 INTEGRITY OF THE EXPERIMENTAL SET-UP

Heat losses. To check if heat losses from pre-evaporators and test-sections are significant, single phase experiments under steady state conditions were conducted using water at different flow rates. The enthalpy difference of water from inlet of the preevaporator, E1 to outlet of the test-section, T2 was computed from measured temperaturesand compared with the electrical energy input to pre-evaporators and test-sections. It can be seen from the set of values given in Table 3.2 that heat losses were negligible.

Single-phase pressure drop: Pressure drop across pre-evaporator, E3 for single-phase water flow was measured under isothermal flow condition. The pressure drop data were compared with the values estimated using Blasius friction factor equation (Knudsen and Katz, 1958) in Figure 3.4. It can be seen from the figure that the agreement is good. However, similar check on the pressure drop data of test-section, T2 showed poor agreement which could be attributed to the presence of thermocouples at the inlet as well as at the outlet of the test-section. Hence pressure drop data across pre-evaporator , E3 was employed in the analysis of two-phase flow.

Single-phase heat transfer coefficients: Heat transfer coefficients for single-phase flow under steady state conditions

TABLE 3.2

HEAT LOSSES FROM THE TEST-SECTIONS AND PRE-EVAPORATORS

S.No.	G kg/m^2 s	Energy input, W	Raise in water Temperature, °C	Enthalpy difference of the water from the outlet to the inlet, W	Heat losses in the percent of the input
1	1689.34	3800	4.26	3816	- 0.4%
2	1689.34	3810	4.24	3790	+ 0.5%
3	748.20	3500	8.82	3496	+ 0.1%
4	301.82	3470	21.65	3460	+ 0.3%

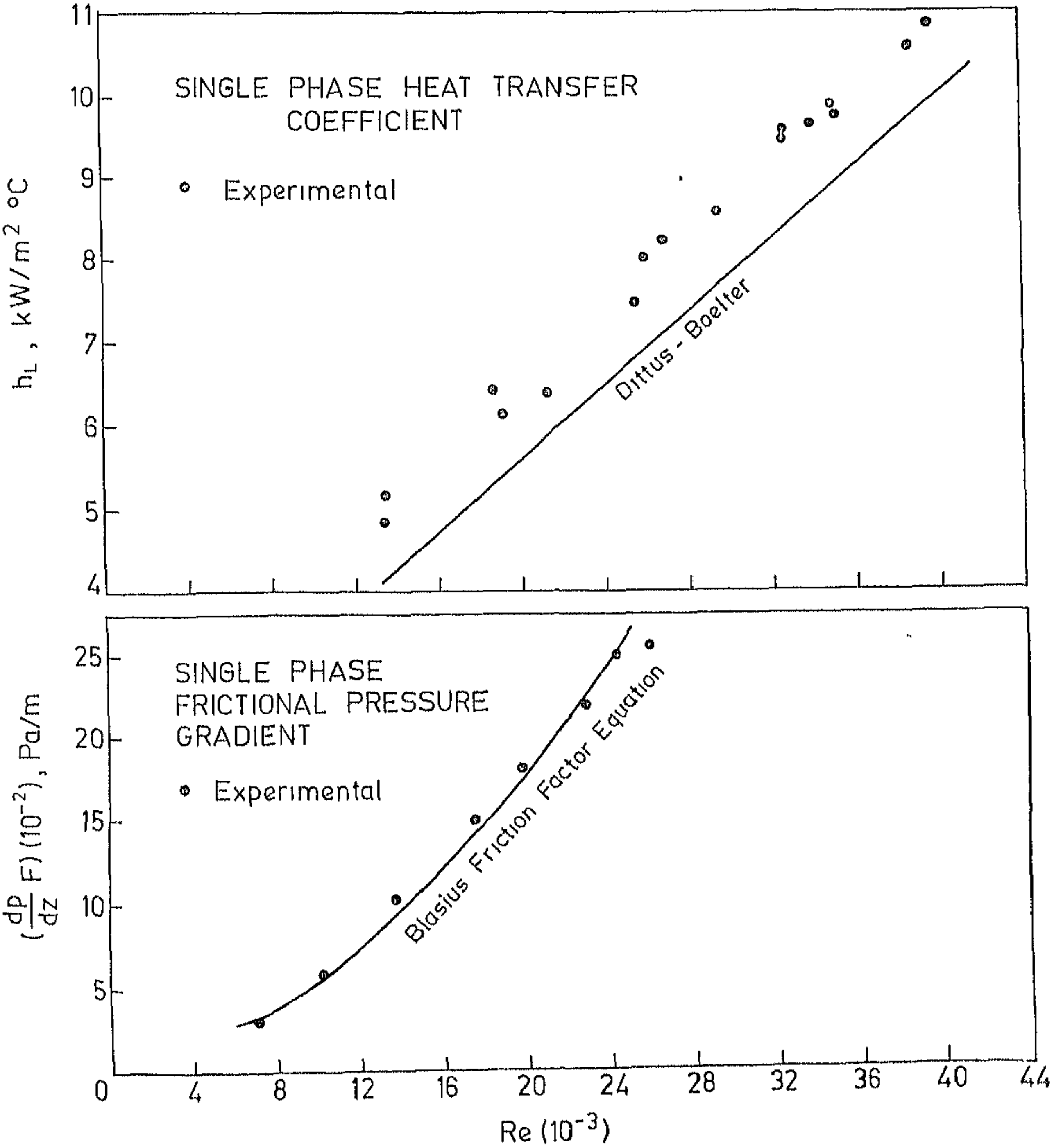


Fig. 3 4 Comparison of the experimental results with the well-known correlation were obtained from the test-section, T2. In order that the temperature profile is fully developed, constant heat flux was maintained in all pre-evaporators and test-sections. The heat transfer coefficients were compared with the Dittus Boelter correlation in Figure 3.4. It can be seen that experimental values are consistantly higher than the predicted. The thermal breaks and the presence of thermocouples at the inlet and outlet of the test-section could have contributed to this difference. However, in convective boiling these effects are expected to be much low due to the highly turbulent nature of two-phase flow.

Reproducibility of heat transfer coefficient in flow boiling:
To check reproducibility of heat transfer data, the runs were repeated at different times. Some typical results are shown in Table 3.3. From the table it can be seen that the reproducibility is good.

REPRODUCIBILITY TESTS ON HEAT TRANSFER DATA

S.No.	Θ degree	G kg/m^2s	x	q/A kW/m^2	T_{Wav} °C	T_b °C	h_{TP} W/m^2 °C
1	0.0	756.0	0.013	236.4	117.50	106.41	21367
	0.0	758.3	0.012	230.1	117.71	106.80	21088
	0.0	759.0	0.014	235.1	116.85	106.21	22090
2	46.0	375.0	0.021	234.5	117.90	104.41	17393
	46.0	378.6	0.020	232.0	118.00	104.38	17038
3	67.5	761.5	0.017	225.2	117.30	105.86	19694
	67.5	756.9	0.017	223.6	116.62	105.30	19834
	67.5	763.0	0.016	220.5	117.24	106.20	19900
4	67.5	756.1	0.008	223.6	117.58	103.93	16381
	67.5	756.9	0.008	223.3	117.72	103.89	16154
	67.5	761.5	0.006	228.9	117.86	103.51	15958

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the experimental results of flow boiling heat transfer, two-phase flow pressure drop and flow patterns in a tube inclined at different angles between horizontal and vertical positions. Using the steam water system experiments were conducted under steady state saturated boiling conditions at atmospheric pressure. The range of experimental parameters covered for heat transfer and pressure drop are given in Table 4.1. The experimental results are compared with those reported in literature for the vertical and horizontal cases. Heat transfer and pressure drop correlations and the flow pattern maps are presented.

4.1 HEAT TRANSFER

4.1.1 Data Reduction Procedure

The methods of computation of boiling heat transfer coefficient, quality and the Lockhart-Martinelli parameter are given below.

Heat Transfer Coefficient: Since thermocouple junctions located on the test-section were about 1 mm away from the inner surface of the tube, the inner surface temperature,

TABLE 4.1

RANGE OF EXPERIMENTAL PARAMETERS

Parameter	For Heat Transfer	For Pressure Drop
Mass Flux, kg/m^2s	125 - 760	125 - 760
Heat Flux, kW/m^2	50 - 230	0 - 100
Quality, %	near zero to 12	near zero to 8
Lockhart-Martinelli parameter	>0.2	>0.3
Re_f	5800 - 35000	5800 - 35000

T_W , was computed from the heat conduction equation

$$T_W = T_{Wm} - q \left[\frac{\ln\left(\frac{r_1+t}{r_1}\right)}{2\pi Lk} \right] \qquad 4.1$$

where q = the rate of heat input to the test-section,

r_1 = inside radius of the tube

t = the distance of the thermocouple junction from the inside surface.

L = the effective heating length of the test-section,

k = the thermal conductivity of copper,

and T_{Wm} = the measured wall temperature.

The heat transfer coefficient, h, was calculated from the equation,

$$h = (q/A)/(T_{Wav} - T_b) \qquad 4.2$$

where A = heat transfer area = $2\pi r_1 L$

T_{Wav} = the average of the inner surface temperatures (averaged over the four locations on the circumference of the tube), and

T_b = liquid temperature obtained by linear interpolation of the inlet and outlet temperatures of the test-section.

Quality: The pressure profile along the heater assembly is required to compute the quality profile. From the pressure drops across various sections and the pressure at the entrance of pre-evaporator E1, the pressure profile was constructed assuming linear variation of pressure in each section.

Taking the flashing and compressibility effects into account, Shoukri et al. (1981) have obtained the following equation for the change of quality with length in the two-phase region.

$$\frac{dx}{dz} = \frac{4(q/A)}{GD\, h_{fg}} - \frac{dp}{dz}\left\{\left[\frac{c_{pf}\, T_s\, v_{fg}}{h_{fg}} + x\, \frac{\partial h_{fg}}{\partial p}\right] \Big/ h_{fg}\right\} \qquad 4.3$$

The quality profile is computed from Equation 4.3 as follows. From the temperature and pressure at the entrance of pre-evaporator E1, the location along the length where liquid gets saturated was found. From this point onwards, the quality profile was computed by numerical intergration of Equation 4.3.

Lockhart-Martinelli Parameter, X_{tt} : The Lockhart-Martinelli parameter, at the location of the wall thermocouples in the test-section, was calculated from the equation,

$$1/X_{tt} = \left(\frac{x}{1-x}\right)^{0.9} \left(\frac{v_g}{v_f}\right)^{0.5} \left(\mu_g/\mu_f\right)^{0.1} \qquad 4.4$$

where v_g = the specific volume of vapor,

v_f = the specific volume of liquid,

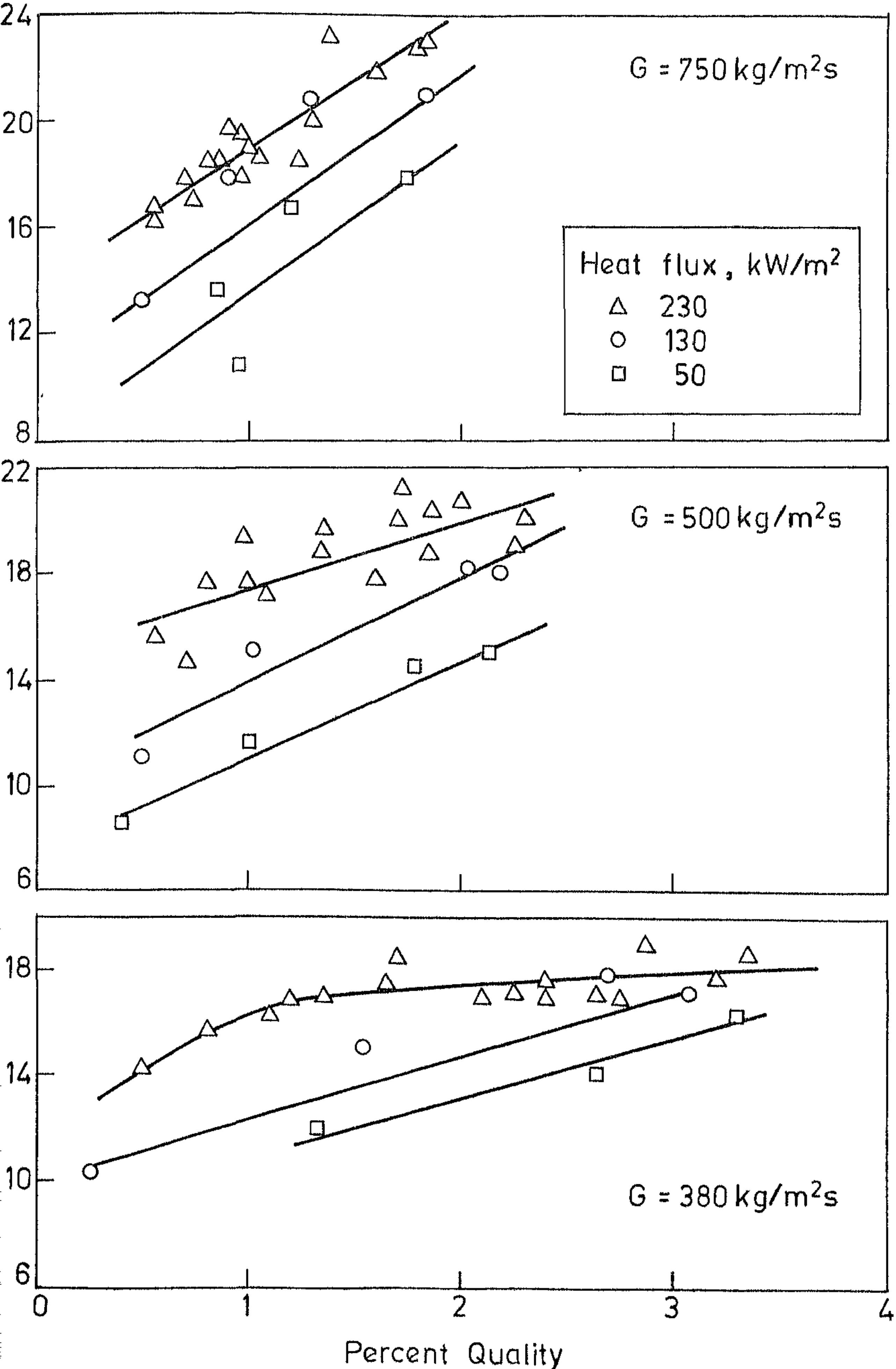
The average Lockhart-Martinelli parameter for the pre-evaporator E3 was obtained by numerical integration of Equation 4.4.

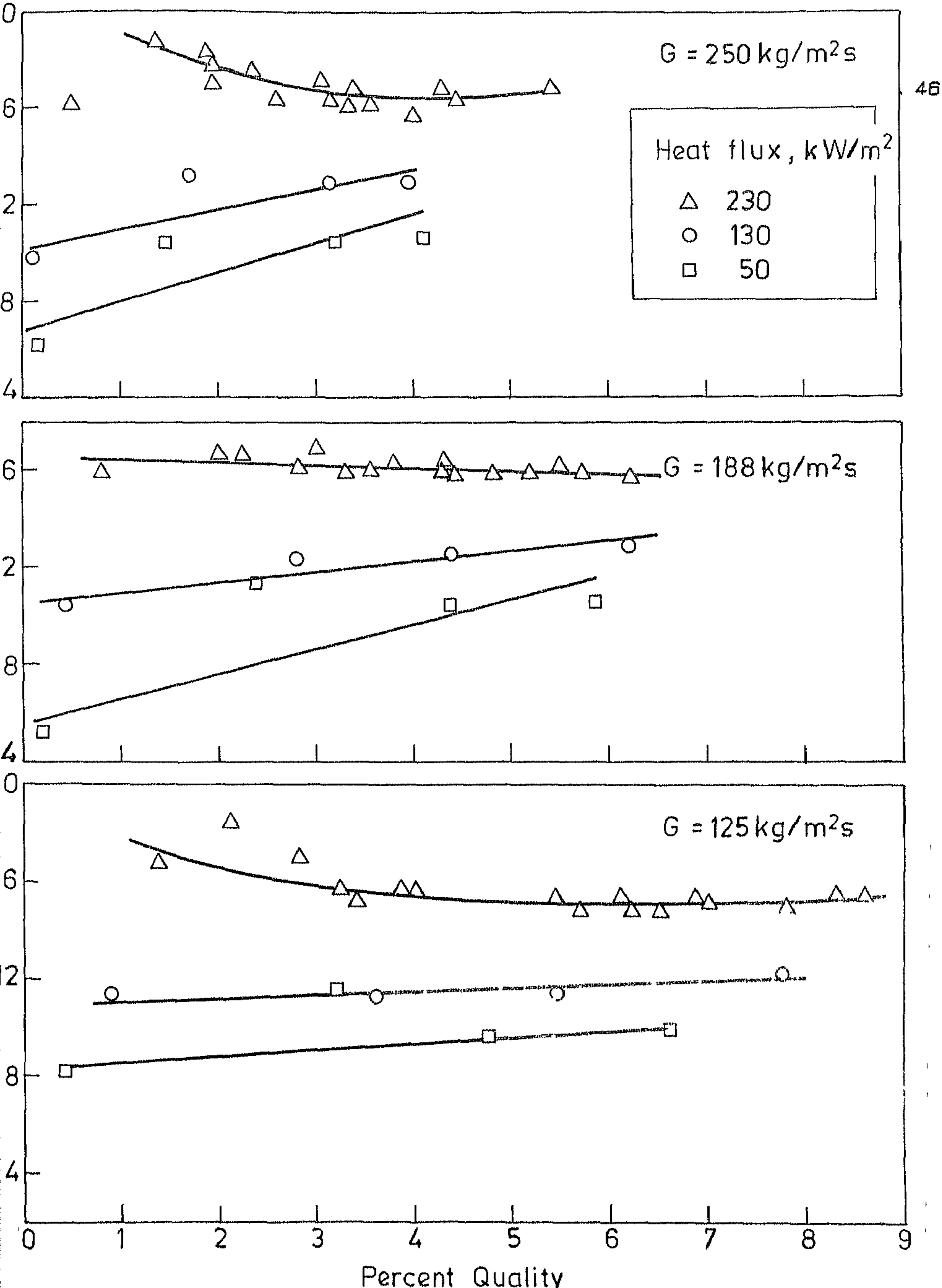
$$X_{tt,av} = \left(\frac{1}{x_o - x_i}\right) \int_{x_i}^{x_o} \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{v_f}{v_g}\right)^{0.5} \left(\frac{\mu_f}{\mu_g}\right)^{0.1} dx \qquad 4.5$$

where x_i and x_o are inlet and outlet qualities , respectively.

4.1.2 Heat Transfer Coefficient

The boiling heat transfer coefficient, h_{TP}, alongwith the experimental parameters like mass velocity, quality, temperature of wall and bulk liquid for all the runs are presented in Appendix B . Figures 4.1A and 4.1B are the typical plots of heat transfer coefficient versus quality with mass velocity and heat flux as parameters for the angle of inclination, $\theta = 30°$. It can be seen from these plots that h_{TP} increased with heat flux. This indicates that the contribution due to


24
20
16
12
8
G = 750 kg/m²s
Heat flux, kW/m²
△ 230
○ 130
□ 50
22
18
14
10
6
G = 500 kg/m²s
18
14
10
6
G = 380 kg/m²s
0
1
2
3
4
Percent Quality


G = 250 kg/m²s
Heat flux, kW/m²
△ 230
○ 130
□ 50
G = 188 kg/m²s
G = 125 kg/m²s
0
6
2
8
4
0
1
2
3
4
5
6
7
8
9
Percent Quality

nucleate boiling is significant if h_{TP} is viewed as the sum of nucleate boiling (microconvection) and forced convective (macroconvection) heat transfer contributions. In general, h_{TP} increased with quality at a constant mass velocity indicating that the macroconvective heat transfer is also significant. However, at lower mass velocities and higher heat fluxes, the increase in h_{TP} with quality was rather less. This trend indicates that microconvection is dominating at higher heat fluxes. Similar trends were also observed for other inclinations and hence they are not presented here.

Figures 4.2A and 4.2B show the effect of angle of inclination on h_{TP} for heat flux 230 kW/m^2 . The data points shown in these graphs were obtained from the smooth curves drawn on the plots of h_{TP} vs quality. It can be seen that the h_{TP} passed through a minimum as the angle of inclination varied from 0° to 90° for G = 750 and 500 kg/m^{2}s. In these cases, the quality is less than 2 % and mass velocities are high, as a consequence the flow pattern was either bubbly or slug flow. When the tube is inclined the vapor bubbles or broken slugs moved close to the upper half of the tube leaving more or less bubble free liquid flow in the lower half. Hence it may

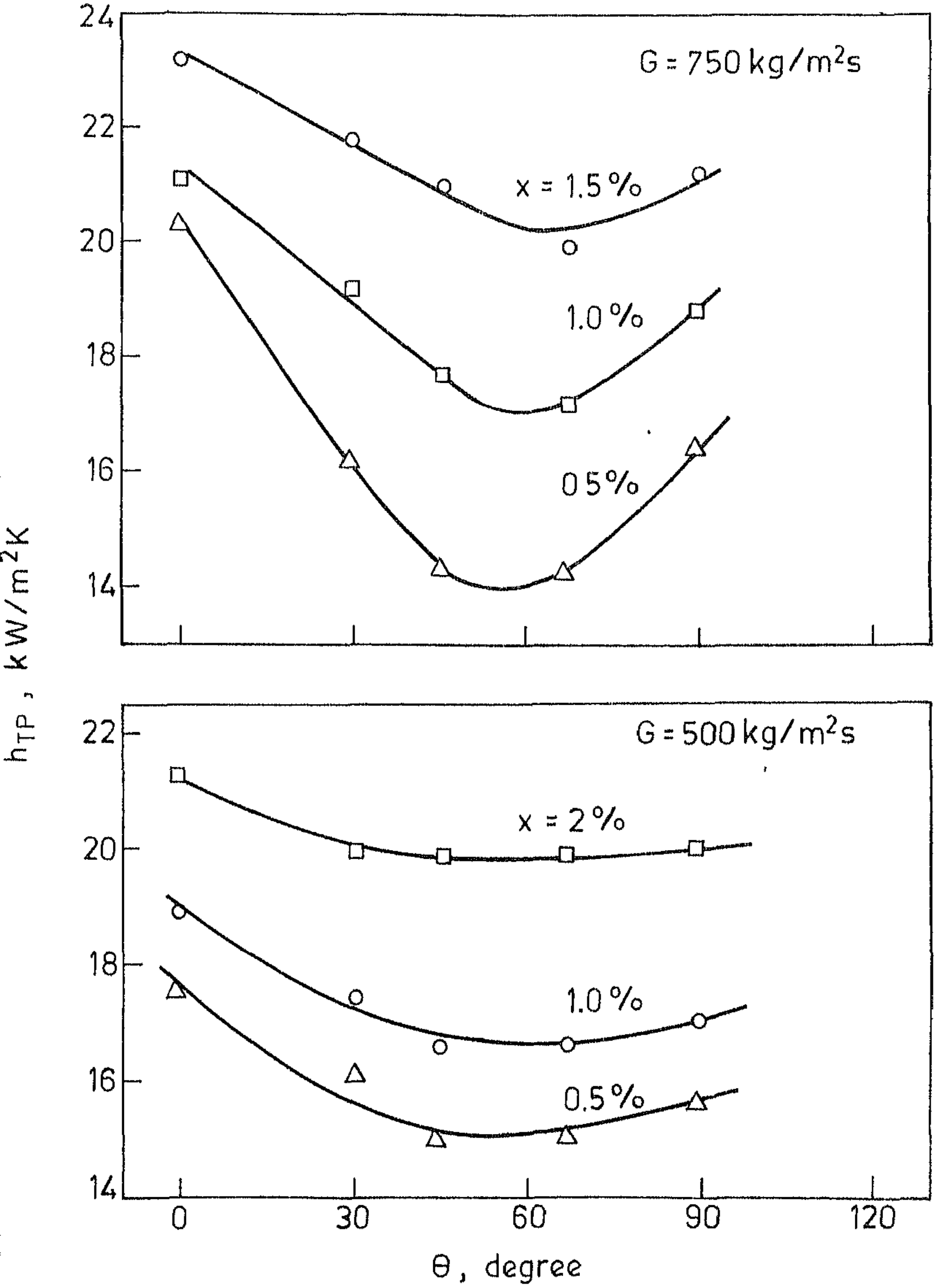


Fig. 4.2A Variation of heat transfer coefficient with θ for $q/A = 230\ kW/m^2$.

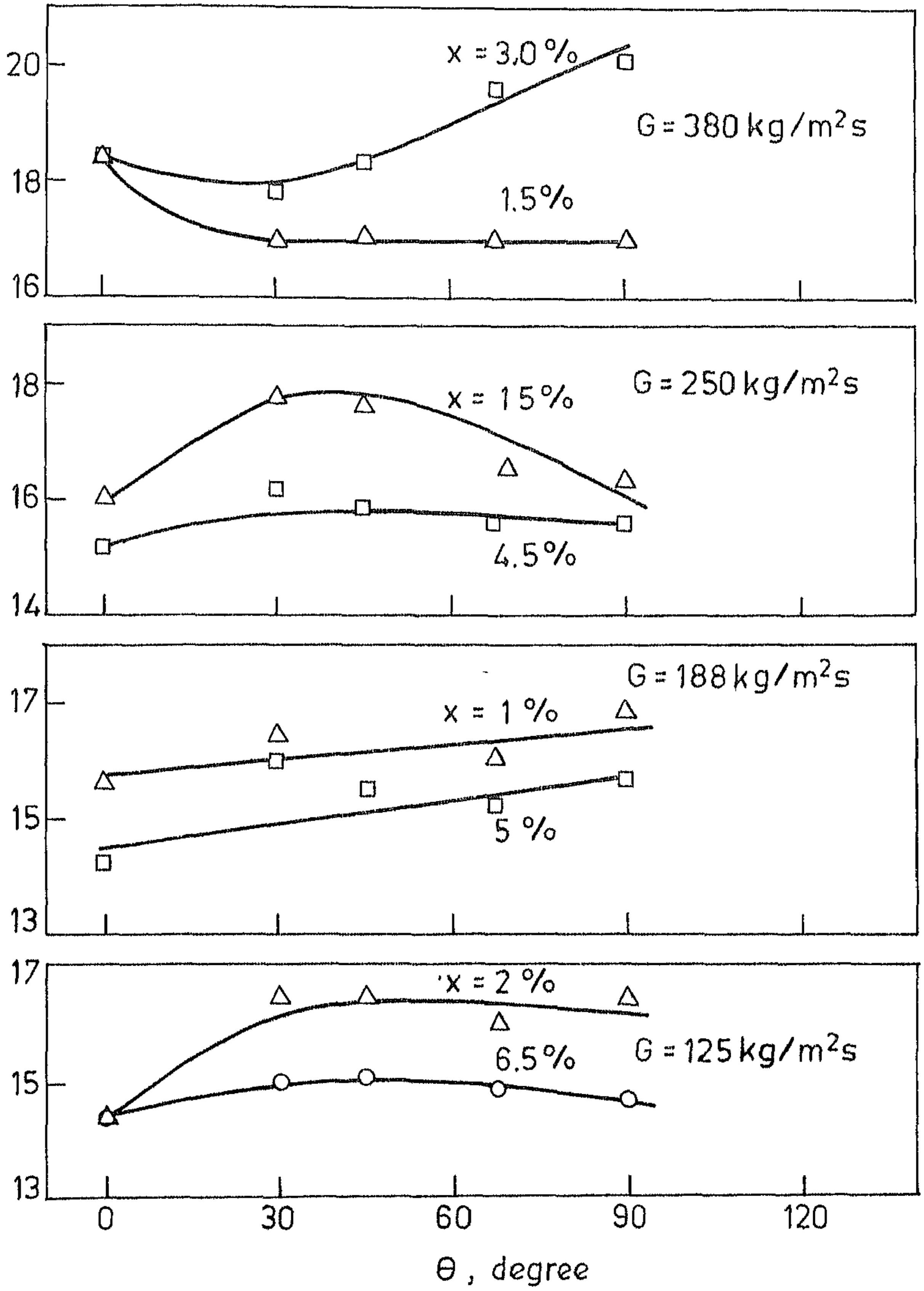


Fig. 4.2B Variation of heat transfer coefficient vith θ for q/A=230kW/m

be expected that macroconvection is dominant in the upper half while microconvection is dominant on the lower side. The relative proportions of these might have changed with the angle of inclination in such a way that h_{TP} is minimum around 50°. In the other cases, the flow pattern is mostly annular and the angle of inclination has a marginal effect.

4.1.3 Comparison and Correlation of Data

The vertical upward flow boiling has been studied extensively and several correlations for heat transfer coefficients are available in the literature. It has been shown that Chen's correlation is superior to the others (Chen, 1966; Collier, 1981). Later Bjorge, Hall and Rohsenow (unpublished) proposed a correlation based on Rohsenow's superposition principle (1952) and claimed better accuracy than the Chen correlation when tested with the water data. Dengler and Addoms (1956) proposed an empirical correlation based on the steam-water data. The range of parameters of the present study are within their experimental parameters. Hence the Dengler and Addoms correlation was also selected for comparison. These correlations are given in Table 4.2. It may be pointed

TABLE 4.2

FLOW BOILING HEAT TRANSFER CORRELATIONS

1. Dengler-Addoms (1956)

$$h_{TP}/h_f = \frac{3.5\ F_{DA}}{X_{tt}^{0.5}}$$

where F_{DA} is correction factor to allow for nucleate boiling and is given by

$$F_{DA} = 0.67 \left[(\Delta T_s - \Delta T_{s,th}) \left(\frac{dp_s}{dT_s} \frac{D}{\sigma} \right)_w \right]^{0.1}$$

where $\frac{dp_s}{dT_s}$ is slope of vapour pressure vs temperature curve at saturation condition, $lb/ft^2\ °F$

2. Chen* (1966)

$$h_{TP} = h_C + h_N$$

where $h_C = 0.023 \left[\frac{G(1-x)D}{\mu_f} \right]^{0.8} \left[\frac{\mu_f\ C_{pf}}{k_f} \right]^{0.4} \frac{k_f}{D}\ F$

$$h_N = 0.00122 \left[\frac{k_f^{0.79}\ C_{pf}^{0.45}\ \rho_f^{0.49}}{\sigma^{0.5}\ \mu_f^{0.29}\ h_{fg}^{0.24}\ \rho_g^{0.24}} \right] \Delta T_s^{0.024}\ \Delta p_s^{0.75}\ S$$

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Table 4.2 (continued)

$$\log F = 0.456 + 0.535 \log 1/X_{tt} + 0.0805 (\log 1/X_{tt})^2$$

For $0.1 < 1/X_{tt} < 10$

$$S = 3.56 - 0.6354 \log (ReF^{1.25})$$

For $2x10^4 < Re_f F^{1.25} < 2x10^5$

3. Bjorge et al.

(A) For high quality region i.e. $\alpha > 0.8$

$$Q = Q_C + Q_B - Q_{B1}$$

$$= Q_C + Q_B \left[1 - \frac{\Delta T_{s,ib}}{\Delta T_s} \right]^3$$

Recommended equations are:

$$\Delta T_{s,ib} = \frac{8 \sigma T_s v_{fg} h_f}{k_f h_{fg}}$$

$$Q_C = \frac{Re_f^{0.9} Pr_f F(X_{tt}) k_f}{F_2 D} \Delta T_s$$

where $F(X_{tt}) = 0.15 \left[1/X_{tt} + 2.0 (1/X_{tt})^{0.32} \right]$

$$F_2 = 5 Pr_f + 5 \ln(1+5 Pr_f) + 2.5 \ln(0.0031 Re_f^{0.812})$$

$Re_f > 1125$

Table 4.2 (continued)

$$F_2 = 5\,Pr_f + 5\ln\left[1 + Pr_f\,(0.0964\,Re_f^{0.585} - 1)\right]$$

$$50 < Re_f < 1125$$

$$F_2 = 0.0707\quad Pr_f\,Re_f^{0.5}$$

$$\text{For } Re_f < 50$$

and

$$Q_B = BM\,\frac{k_f^{0.5}\,\rho_f^{17/8}\,Cp_f^{19/8}\,\rho_g^{1/8}\,h_{fg}^{1/8}}{(\rho_f - \rho_g)^{9/8}\,\sigma^{5/8}\,T_s^{1/8}}\left[\frac{g(\rho_f - \rho_g)}{g_c\,\sigma_0}\right]^{0.5}\Delta T_s^3$$

where BM is dimensionless constant.

(B) Subcooled and low quality regime i.e. $\alpha < 0.8$

$$Q = \left\{Q_C^2 + Q_B^2\left[1 - \left(\frac{\Delta T_{s,ib}}{\Delta T_s}\right)^3\right]^2\right\}^{1/2}$$

Recommended equations:

$$Q_{jb} = \frac{h_C}{1-N}\left(\frac{1}{4\gamma N} + \Delta T_{sc}\right)$$

$$\text{For } r_{tang} > 10^{-6}\ \text{m}$$

$$Q_{ib} = h_C\,\Delta T_{sc} + \frac{1}{2\gamma}\left(1 + \sqrt{1 + 4\gamma T_{sc}}\right)$$

$$\text{For } r_{tang} < 10^{-6}\ \text{m}$$

Table 4.2 (continued)

where

$$\Gamma = k_f \, h_{fg} / (8 \sigma T_s \, v_{fg} \, h_C)$$

$$N = h_C \, r_{max} / k_f$$

$$r_{tang} = 4 \sigma \, T_s \, v_{fg} / (h_{fg} \, \Delta T_{s,ib})$$

r_{max} = radius of largest cavity = 10^{-6} m

$$\frac{h_C \, D}{k_{fb}} = 0.023 \left(\frac{GD}{\mu_f} \right)^{0.8} \left(\frac{\mu_f \, c_{pfb}}{k_{fb}} \right)^{1/3}$$

subscript b in the above equations indicates that properties should be evaluated at the liquid bulk temperature, T_b, and all other properties should be evaluated at the film temperature, $(T_w + T_b)/2$. ΔT_{sc} is degree of subcooling, $(T_s - T_b)$.

$$Q_C = h_C \, (\Delta T_s + \Delta T_{sc})$$

$$T_{s,ib} = \frac{Q_{ib}}{h_C} - \Delta T_{sc}$$

* Original graphical correlation was fitted by polynomials

out that Bjorge et al. gave two sets of correlations for h_{TP} ; one for the high quality regime, that is $\alpha > 0.8$, and another for $\alpha < 0.8$. As the void fraction is not known and as the accuracy of the available void fraction correlations is uncertain, h_{TP} was estimated from both sets of correlations. It was found that the correlation corresponding to the higher quality region gave less deviation from the data, and this correlation was used for comparison. The above three correlations are compared with the present vertical flow boiling data in Figures 4.3, 4.4 and 4.5. It can be seen that the Chen correlation is superior to the others. The scatter in the case of Dengler-Addoms appears to be high. Besides being accurate and applicable over a wide range of physical properties, the Chen correlation is based on sound physical arguments and hence it has been adopted to correlate the data.

The functions F and S in the Chen correlation can be expected to vary with the angle of inclination for the following reasons. Chen showed that F is related to the two-phase frictional multiplier. Later, it will be shown in section 4.2.3 that the two-phase frictional pressure drop is a function of the angle of inclination. Spedding et al. (1982) have also observed that the two-phase

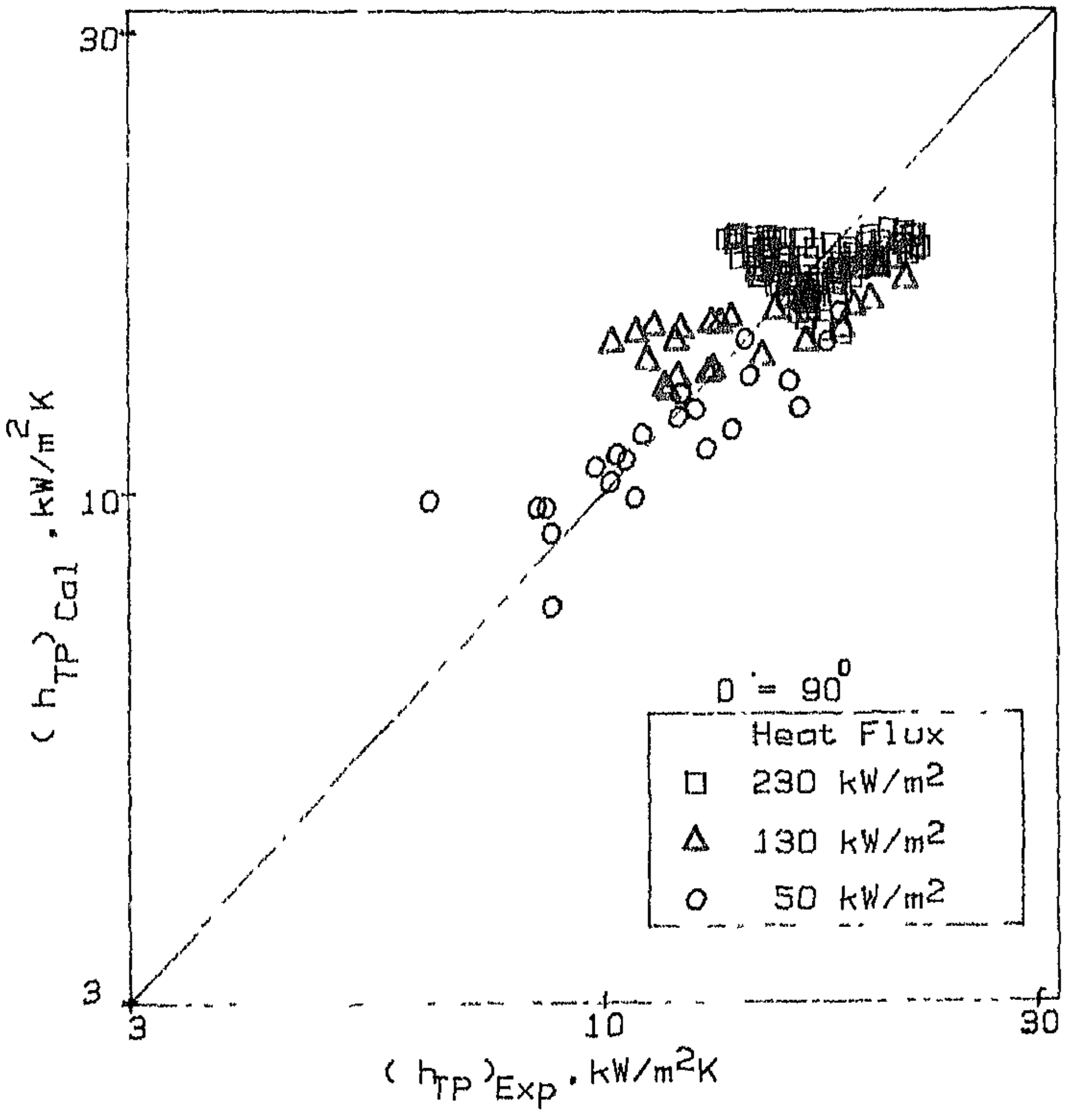


FIG 4.3 Comparison of Experimental Data with the Chen correlation

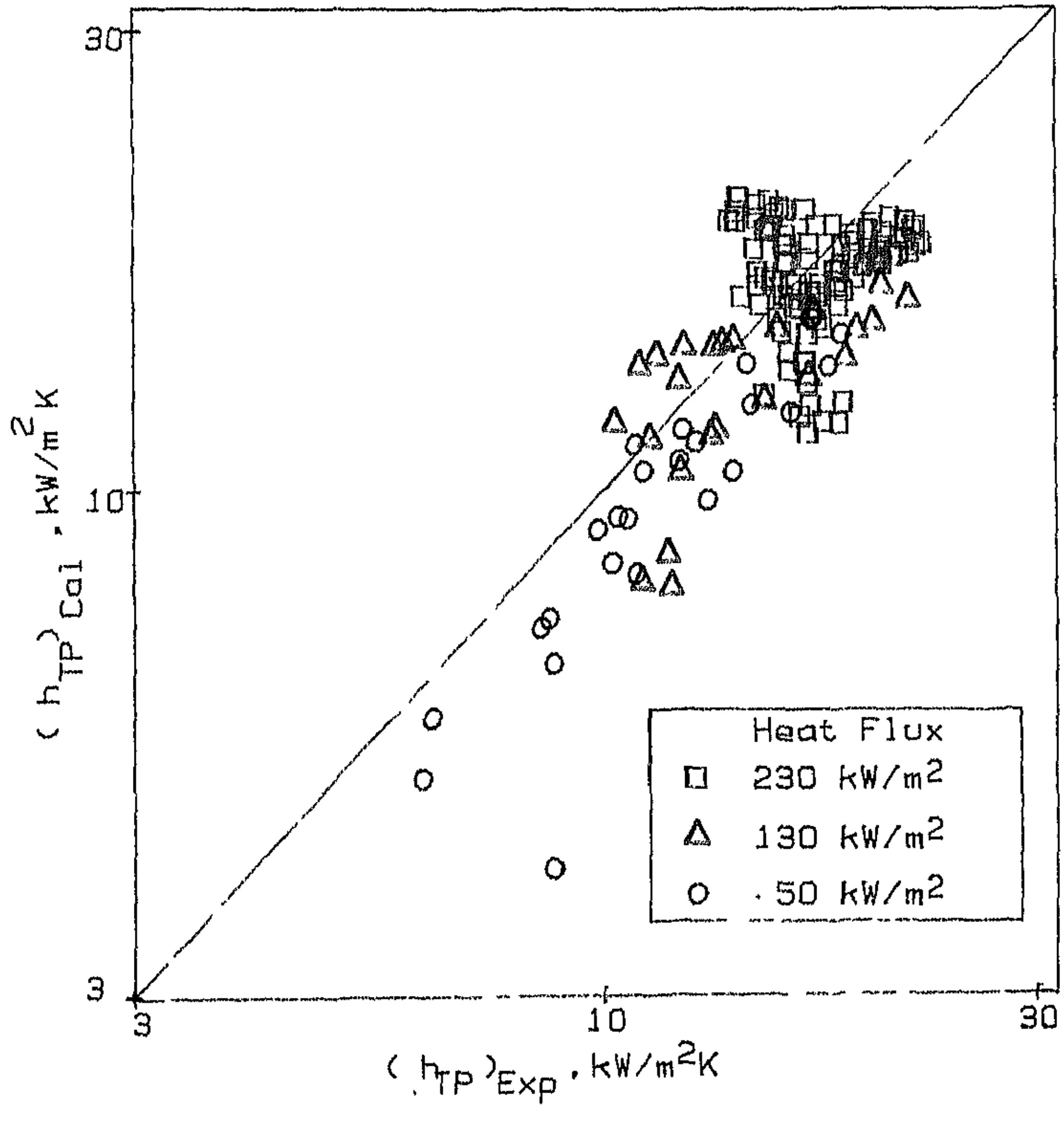


FIG 4.4 Comparison of Experimental Data with the Bjorge et al. Correlation

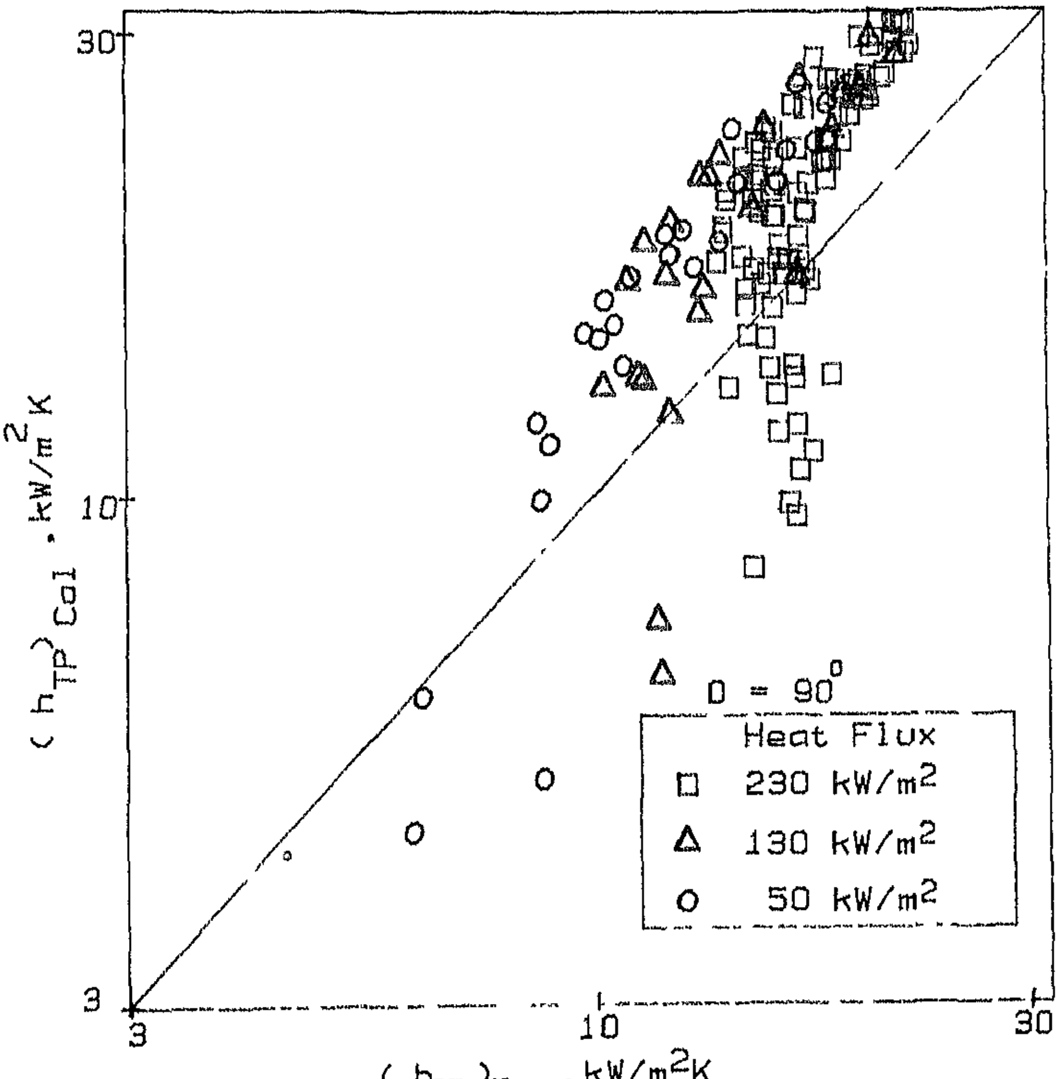


FIG 4.5 Comparison of Experimental Data with the Dengler-Addoms Correlation

frictional pressure drop is influenced by the angle of inclination. Hence, the function F is expected to depend on the angle of inclination. Chen explained that the suppression factor arises because of non-uniform superheat of the liquid over a growing bubble. Bar-Cohen et al. (1983), Styikovich and Mipolskisi (1950) and Stenier and Schlunder (1976) have reported circumferential variation in wall temperature in the case of horizontal flow boiling. Fletcher and McManus (1968) reported circumferential variation in heat transfer coefficient for air-water flow in horizontal tubes. This variation may be attributed to the asymmetric distribution of voids over a cross-section of the tube. Hence it is expected that there can be a circumferential variation in temperature gradient in inclined tubes. As a consequence the suppression factor may vary along the circumference at any given cross section of tube while it is expected to be uniform in the case of vertical flow boiling. Therefore, the function S is also expected to vary with inclination.

In the present investigation the dependence of S and F on the angle of inclination has been explored. The functions S and F have been estimated adapting the iterative scheme suggested by Chen after suitably modifying it for computation on digital computer. Based on the preliminary calculation, for the range of parameters involved, the functions F and S are assumed to be of the form:

$$\log F = C_1 + C_2 \log (1/X_{tt}) \tag{4.6A}$$

$$S = C_3 + C_4 \log (Re.F^{1.25}) \tag{4.6B}$$

where C_1, C_2, C_3 and C_4 are constants. The set of values of C_1, C_2, C_3 and C_4 that minimize the average deviation was found for each of the inclinations. The algorithm which was employed for evaluation of the constants, is presented in Appendix A. The constants C_1, C_2, C_3 and C_4 showed a regular variation with the angle of inclination as can be seen from Figures 4.6A and 4.6B. These curves were fitted to polynomial functions of θ and are given below.

$$\begin{aligned}
C_1 &= 0.4507 + 1.2x10^{-3}\theta - 5.27x10^{-6}\theta^2 \\
C_2 &= 0.1543 + 1.51x10^{-2}\theta - 2.625x10^{-4}\theta^2 + 1.444x10^{-7}\theta^3 \\
C_3 &= 1.224 + 9.73x10^{-3}\theta + 2.458x10^{-4}\theta^2 \\
C_4 &= -0.1483 - 1.972x10^{-3}\theta - 5.556x10^{-5}\theta^2 \qquad 4.7
\end{aligned}$$

The comparison of the estimated and experimental h_{TP} is shown in Figure 4.7. The average deviation is

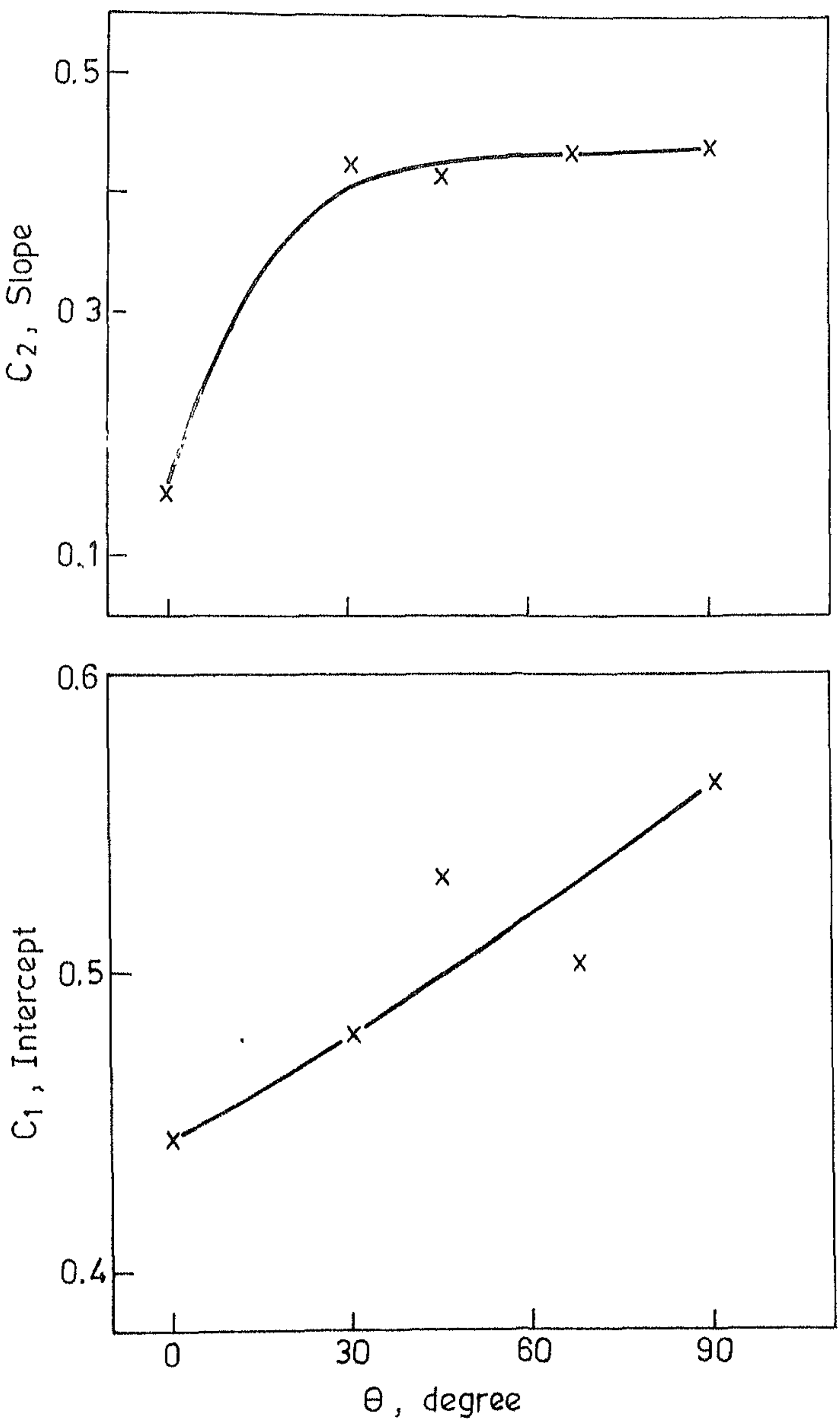


Fig. 4.6A Variation of C and C with θ

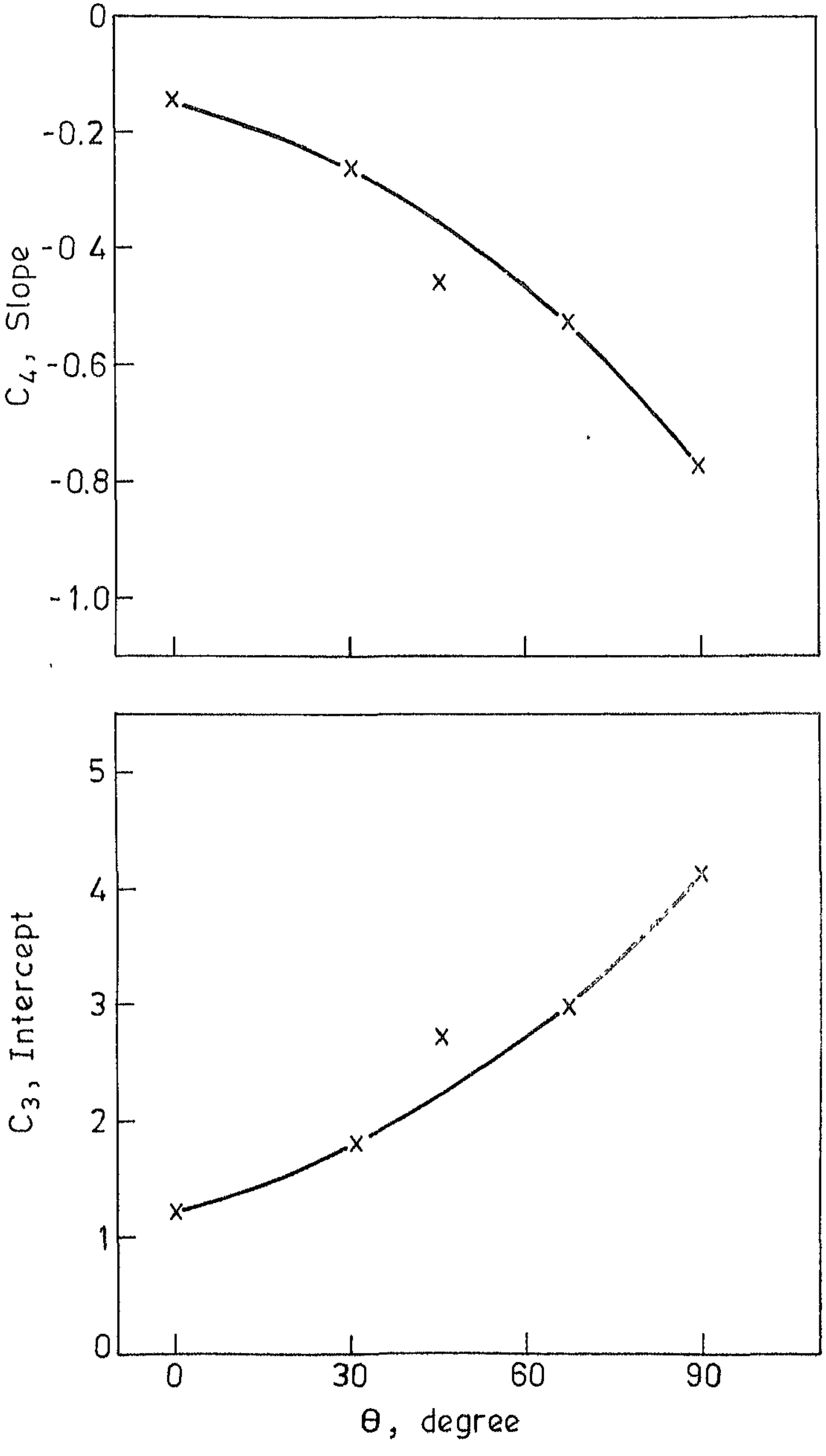


Fig. 4.6B Variation of C_3 and C_4 with θ.

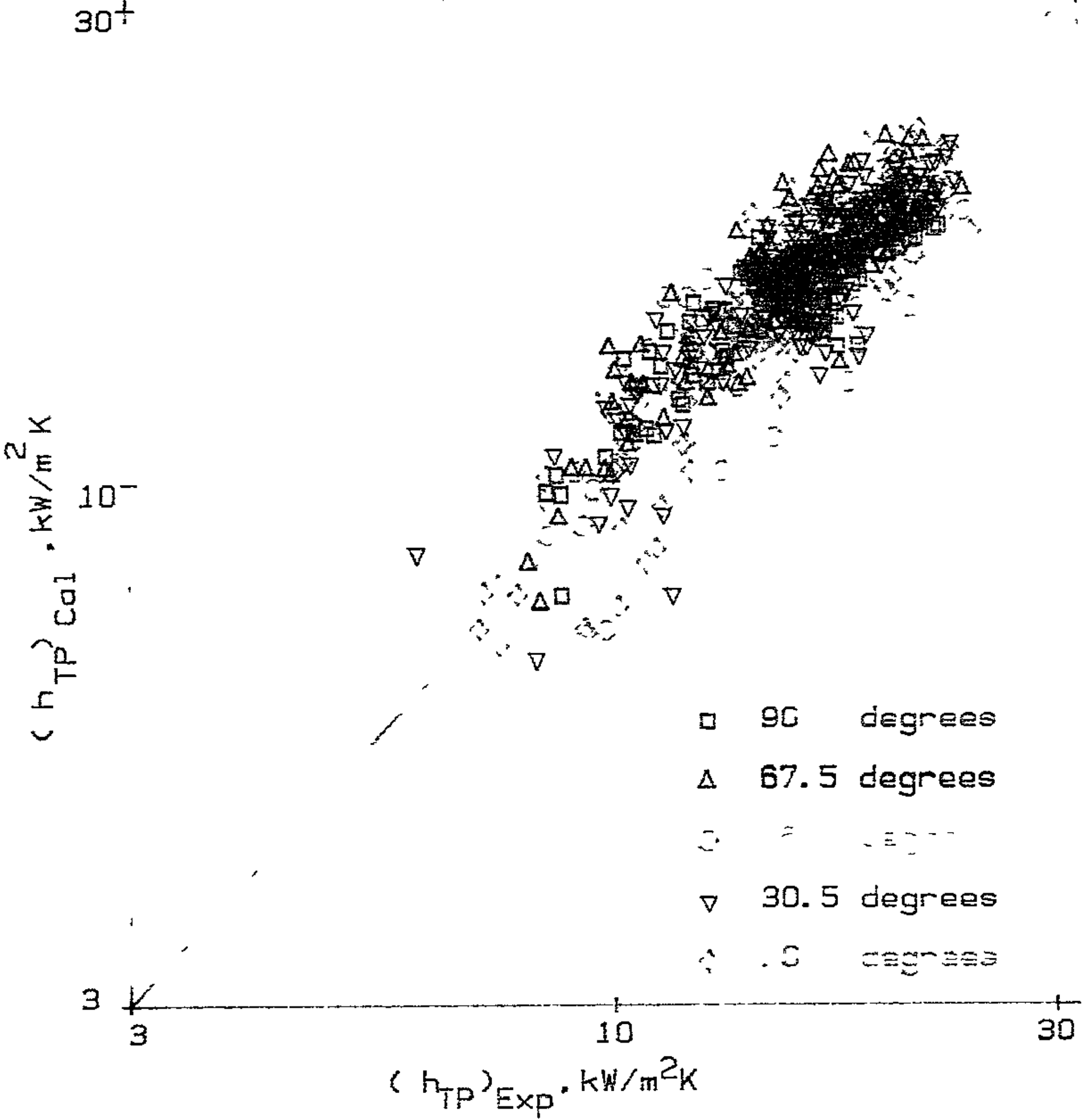


FIG 4.7 Comparison the Proposed Heat Transfer Correlation with the Experimental Data

9.2 % and the mean is 0.84 %. It was found that 75 % of the points are predicted with an average deviation of 6.5 %.

Based on the Reynolds analogy, Chen (1966) derived a relation between F and the two-phase frictional multiplier as

$$F = \phi_f^{0.89} \qquad 4.8$$

Now only function S is to be determined from the heat transfer data. The parameter F was evaluated from the frictional pressure drop correlation (Equation 4.18) based on the data obtained in the present work (described in section 4.2.5) and the factor S was evaluated for each run from the equation

$$S = (h_{TP} - \phi_f^{0.89x1.25}\ h_f)/\ h_N \qquad 4.9$$

The new values of constants C_3 and C_4 of Equation 4.6B are evaluated from the set of S values using the method of weighted least squares for each of the inclinations and are given in Table 4.3. The correlations are compared with the experimental data and the average and mean deviations are reported in Table 4.3. Though deviations are slightly larger than when both F and S were determined from the heat transfer data, the relatively good fit lends support to the theoretical approach based on the analogy.

TABLE 4.3

VALUES OF C_3 AND C_4 EVALUATED BASED ON REYNOLDS ANALOGY AND COMPARISON OF THE CORRELATION WITH THE EXPERIMENTAL DATA

Angle of inclination	C_3	C_4	Percent Deviation Average	Percent Deviation Mean
90.0	4.186	- 0.790	12.5	- 6.9
67.5	1.375	- 0.215	12.8	- 7.5
46.0	3.911	- 0.728	16.0	-12.2
30.5	2.629	- 0.477	13.0	- 7.3
0.0	2.224	- 0.389	11.8	- 7.4

4.2 PRESSURE DROP

As often referred to in the two-phase flow literature, the pressure gradient is referred as pressure drop of this work. The pressure drop of two-phase flow can be expressed as a sum of frictional, gravitational and accelerational pressure drop components. The total pressure drop can be written as

$$\frac{dp}{dz} = \left(\frac{dp}{dz}F\right) + \left(\frac{dp}{dz}G\right) + \left(\frac{dp}{dz}A\right) \qquad 4.10$$

where the subscripts F, G and A stand for frictional, gravitational and accelerational terms, respectively. For a steady one dimensional two-phase flow the above equation can be expressed as

$$\frac{dp}{dz} = \varphi_f^2\left(\frac{dp}{dz}F\right)_f + G\frac{d}{dz}\left[xv_g + (1-x)v_f\right] + \left[\alpha\rho_g + (1-\alpha)\rho_f\right]\sin\theta$$

Alternatively,

$$\frac{dp}{dz} = \varphi_f^2\left(\frac{dp}{dz}F\right)_f + G^2\frac{d}{dz}\left[\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_f}\right] + \left[(\alpha\rho_g + (1-\alpha)\rho_f\right]\sin\theta \qquad 4.11$$

The pressure drop over a length of the tube can be obtained as

$$\Delta p = \int_0^L \phi_f^2 \left(\frac{dp}{dz}F\right) dz + G^2 \left[\frac{x^2}{\alpha \rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_f}\right]_{x_i}^{x_o} + \int_0^L \alpha \rho_g + (1-\alpha)\rho_f \quad \sin\theta \; dz \qquad 4.12$$

In the following sections, the total pressure drop and frictional pressure drop data are presented.

4.2.1 Total Pressure Drop

As the quality increases the gravitational pressure drop decreases, while the frictional pressure drop increases. The accelerational pressure drop increases depending on the variation of quality with length. As a consequence the total pressure drop may either increase or decrease with quality depending on the angle of inclination. Figures 4.8A and 4.8B show the variation of the total pressure drop with quality at different angles of inclination for G = 250 kg/m^{2}s. It can be seen that the total pressure drop at first decreased with increase in quality and then increased; except in the case of horizontal flow where it increased with quality because the gravitational pressure drop was zero. Similar trend

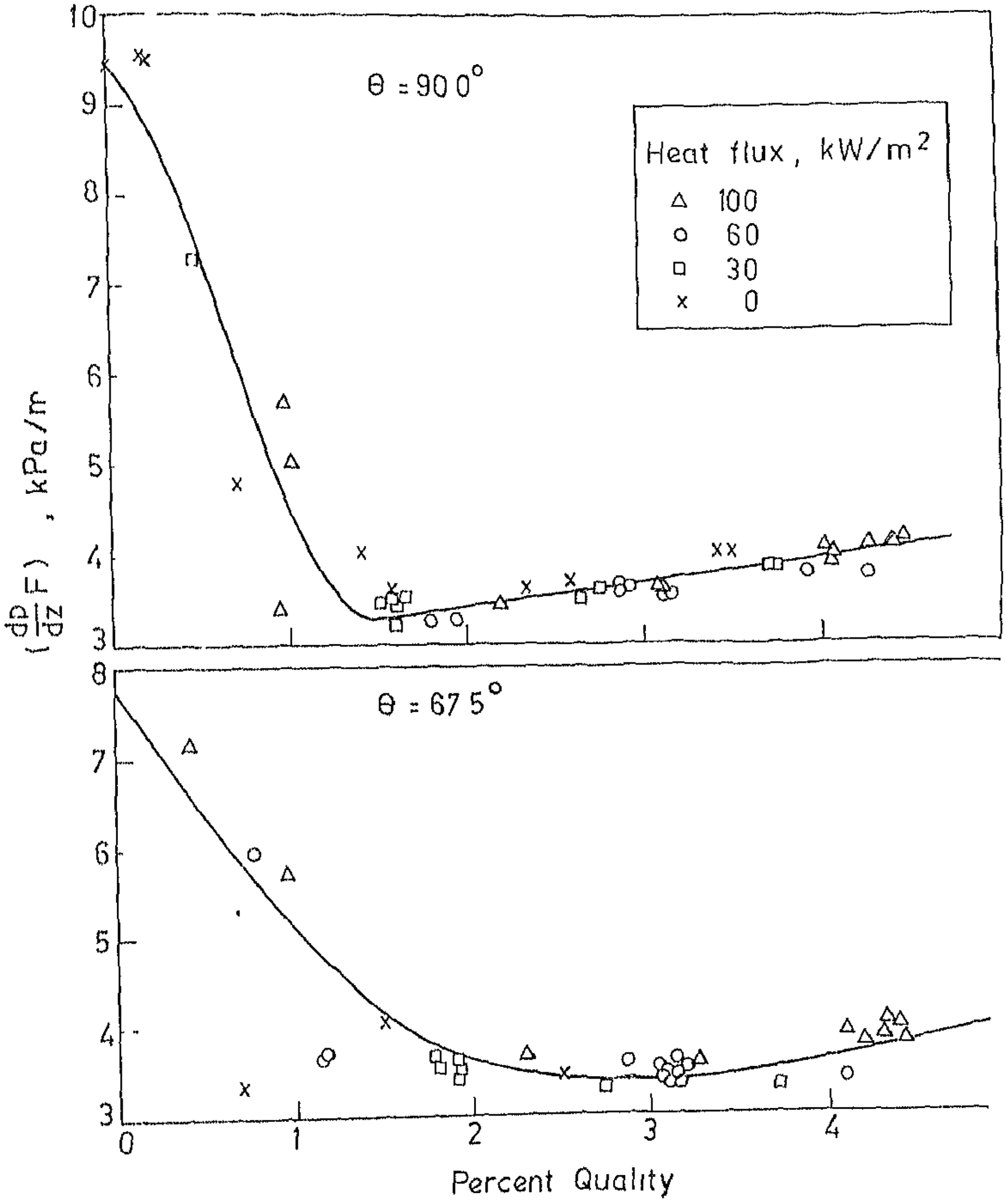


Fig 4 8A Total pressure drop versus quality for G = 250 kg/

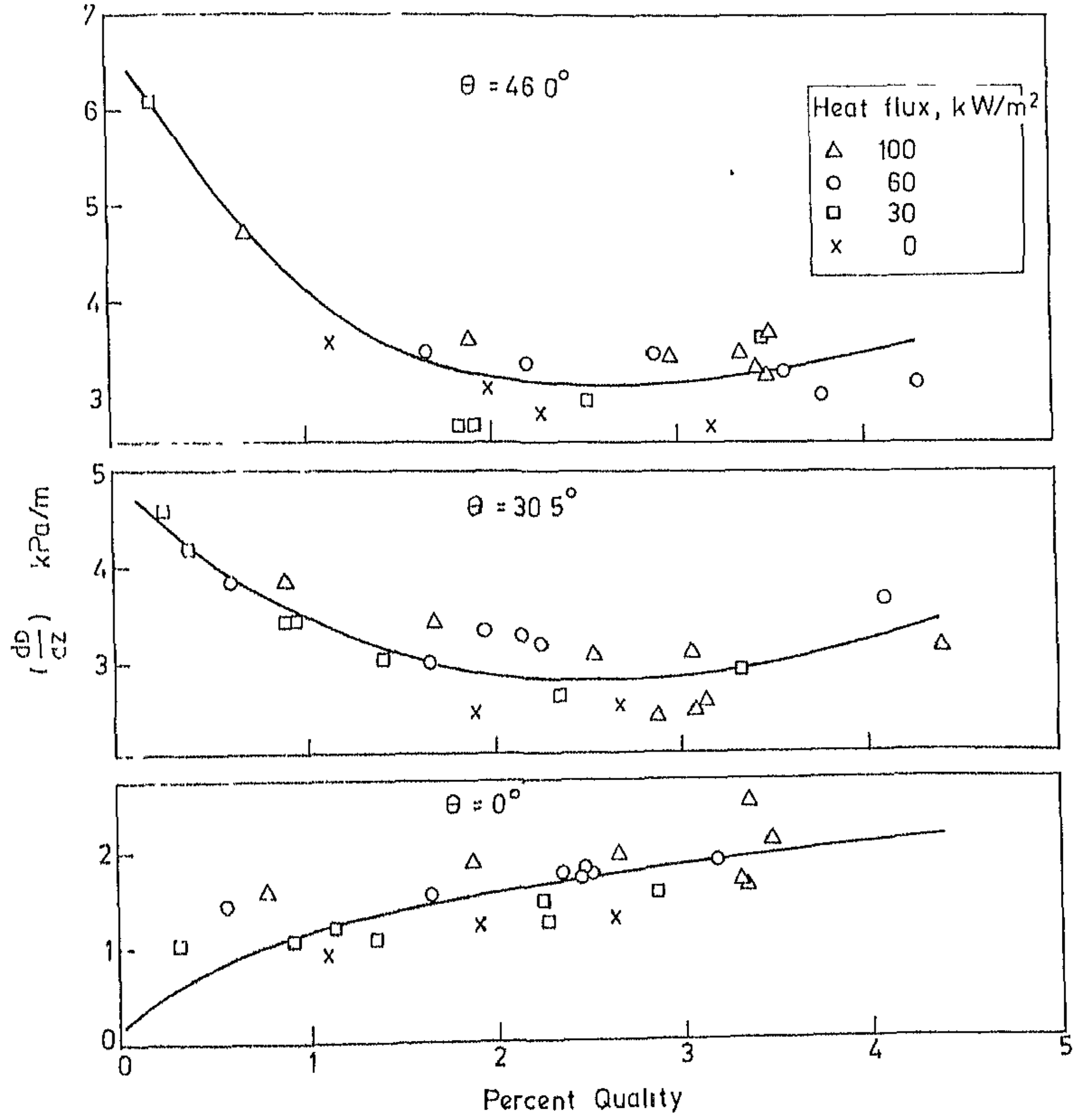


Fig 4 8B Total pressure drop versus quality for G = 250kg/m²s was observed for mass velocities 380, 188 and 125 kg/m^{2}s. In the case of higher mass velocities (i.e. 750 and 500 kg/m^{2}s) the total pressure drop was observed to increase with quality.

4.2.2 Determination of Void Fraction and Frictional Pressure Drop

To find the frictional pressure drop from the total, the gravitational and accelerational pressure drops must be known. The evaluation of these requires the void fraction along the length of the tube. Several void fraction correlations are available in the literature for vertical flow conditions. Some of the widely used correlations are that of Hughmark (1962), Beggs and Brill (1973) and Lockhart and Martinelli (1949). Dengler and Addoms (1956) and Isbin et al. (1957) have reported void fraction correlations which are based on their steam-water flow data, and their experimental parameters are within the experimental range of the present work. These void fraction correlations are presented in Table 4.4. In Figure 4.9, these correlations are compared over the quality range of interest. It can be seen that the discrepancies among these are quite large. Since void fraction has not been measured in the present work, a

TABLE 4.4

VOID FRACTION CORRELATIONS EMPLOYED

1. Dengler-Addoms* (1956)

$$\alpha = 0.88 - 0.187\ X_{tt} + 0.015\ X_{tt}^2 - 4.2 \times 10^{-4}\ X_{tt}^3\ ;$$

For $1 < X_{tt} \leq 10$

$$\alpha \doteq 0.99 - 0.26\ X_{tt} - 0.021\ X_{tt}^2\ ;$$

For $0.06 \leqq X_{tt} \leqq 1$

2. Tobin et al.* (1957)

$$\alpha = 0.72 + 6.5\ x - 50.2\ x^2\ ;$$

For $0.02 < x \leq 0.04$

$$\alpha = 0.42 + 61.6\ x - 3558\ x^2 + 75188\ x^3;$$

For $0.003 < x \leq 0.02$

3. Hughmark* (1962)

$$\alpha = \rho_f K/\rho_g \ / \ (\frac{1}{x} - 1 + \rho_f/\rho_g)$$

$$K = 0.733 + 0.0056\ Z - 5.5 \times 10^{-5}\ Z^2 + 2 \times 10^{-7}\ Z^3;$$

For $Z > 10$

$$K = 0.168 + 0.313\ Z - 35.73 \times 10^{-3}\ Z^2 + 1.39 \times 10^{-3}\ Z^3$$

$1.5 < Z \leq 10$

where $Z = Re^{1/6}\ Fr^{1/8} / \rho_f^{0.25}$

$Re = DG / \left[(1-\alpha)\mu_f + \alpha\,\mu_g \right]$

$Fr = V_T^2 / gD$

Table 4.4 (continued)

4. Beggs and Brill (1973)

$$(1-\alpha)_\theta = B\,(1-\alpha)_0$$

where $B = 1 + \beta\left(\sin 1.8\theta - \frac{\sin^3 1.8\theta}{3}\right)$

and β and $(1-\alpha)_0$ are obtained from the relations,

$$(1-\alpha)_0 = \frac{0.98C_L^{0.4846}}{Fr^{0.0868}} \quad ; \beta = (1-C_L)\ \ln \frac{0.011\ N_V^{3.539}}{C_L^{3.768}\ Fr^{1.614}}$$

For segregated flow

$$(1-\alpha)_0 = \frac{0.845C_L^{0.5351}}{Fr^{0.0173}} \quad ; \beta = (1-C_L)\ \ln\left[\frac{2.96C_L^{0.305}\ Fr^{0.0978}}{N_V^{0.4473}}\right]$$

For Intermittent flow

$$(1-\alpha)_0 = \frac{1.065C_L^{0.5824}}{Fr^{0.0609}} \quad ; \beta = 0$$

For Distributed flow

where

$$N_V = V_{s\ell}\left(\frac{\rho_\ell}{g\sigma}\right)^{0.25}$$

$$C_L = V_{s\ell}/V_T$$

and flow regimes are determined on the basis of two parameters,

$$L_1 = \exp\left[-4.62 - 3.757x - 0.481\ x^2 - 0.0207\ x^3\right]$$

$$L_2 = \exp\left[1.061 - 4.602\ x - 1.609\ x^2 - 0.179\ x^3 + 0.000635\ x^5\right]$$

Table 4.4 (continued)

where $x = \ln C_L$

Flow regimes are classified as:

if $Fr < L_1$ flow is segregated;

$Fr > L_1$ and L_2 flow is distributed,

and $L_1 < Fr < L_2$ flow is intermittent

5. Lockhart-Martinelli (Shoukri et al., 1981)

$$\alpha = (1 + X_{tt}^{0.8})^{-0.378}$$

* The original graphical correlation were fitted by polynomials.

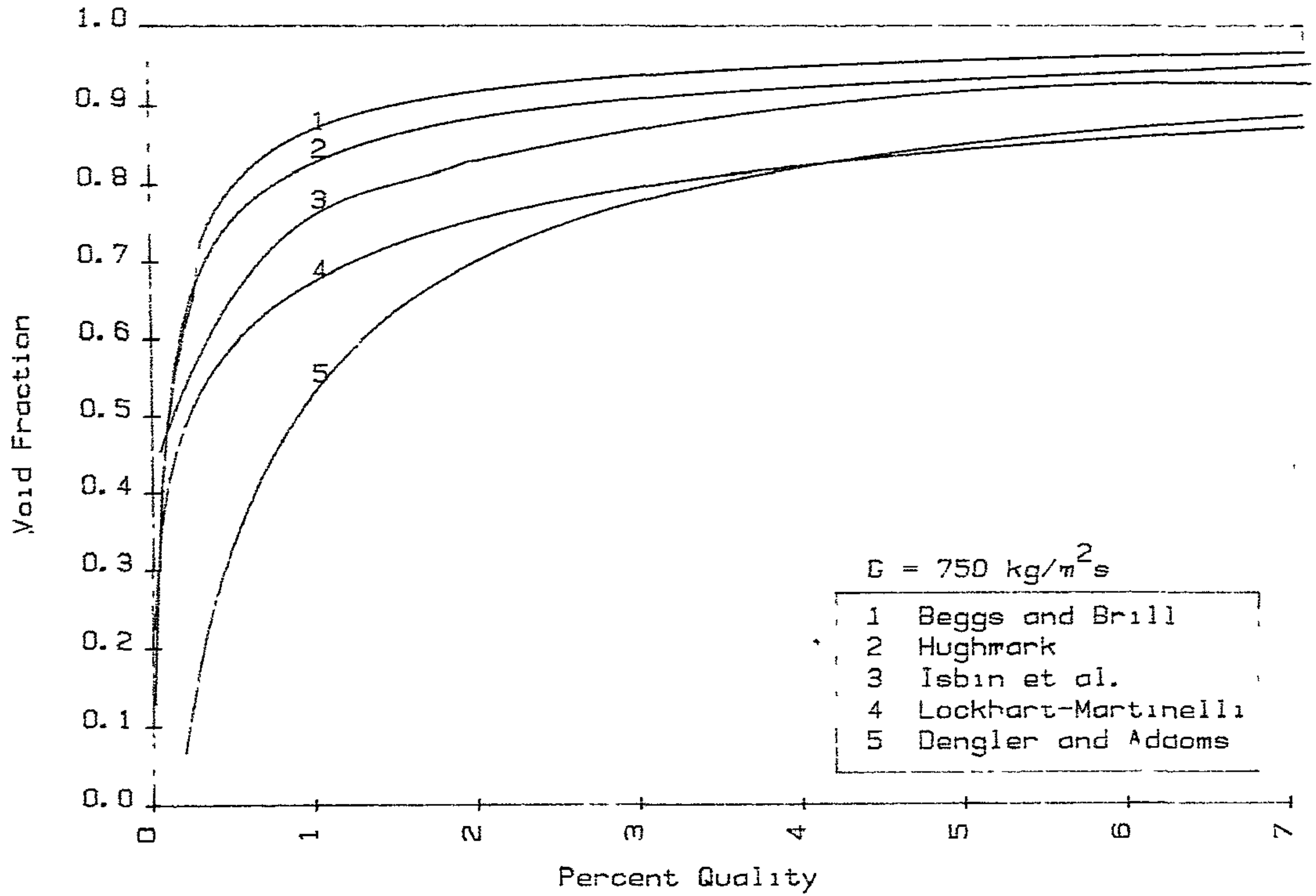


FIG 4.9 Comparison of Void Fraction Correlations

direct method of selection of the correlation, which would represent the void fraction closely, could not be done. In view of this, an indirect method was employed which is given below.

The frictional pressure drop was estimated for the vertical upward flow employing each of those void fraction correlations. The pressure drop thus computed was compared with that estimated using the Baroczy correlation and are shown in Figure 4.10A to 4.10E. The frictional pressure drop computed using the Dengler-Addoms correlation compared well with the estimated than the rest of the correlations. It is to be expected because the Dengler-Addoms correlation is the only one which is based on the data obtained under flow boiling conditions. The widely acclaimed Hughmark correlation appears to be good only at low mass velocities but deviations are significant at higher flow rates. However, it may be pointed out that the agreement does not automatically reflect the superiority of the correlation over the others; rather it should be considered to be compatible with the Baroczy correlation. In view of the above, the Dengler-Addoms correlation has been chosen for the vertical case.

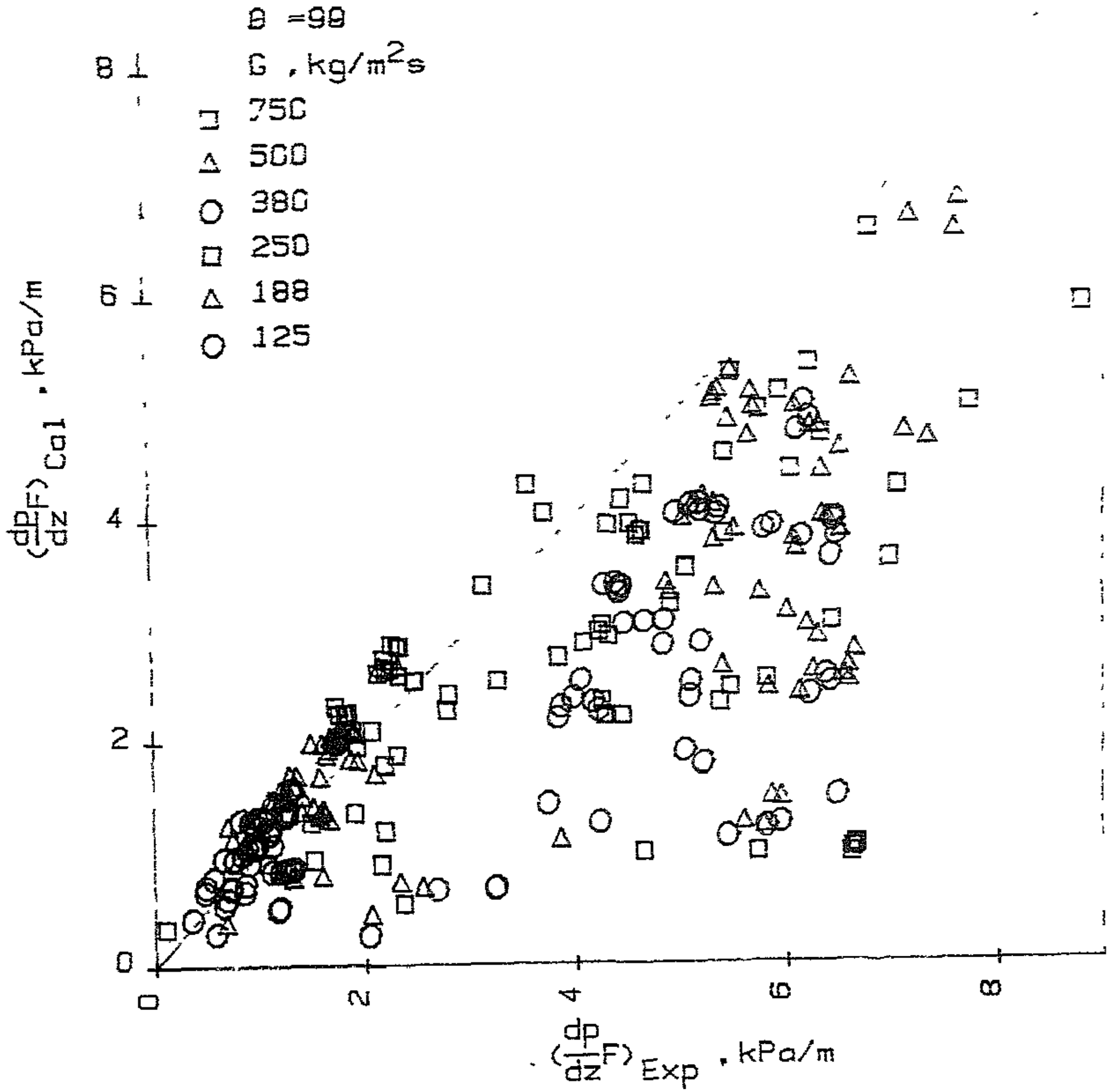


FIG 4.10A Comparison of Frictional Pressure Drop obtained Using the Hughmark Void Fraction Correlation with that Computed from the Baroczy Correlation

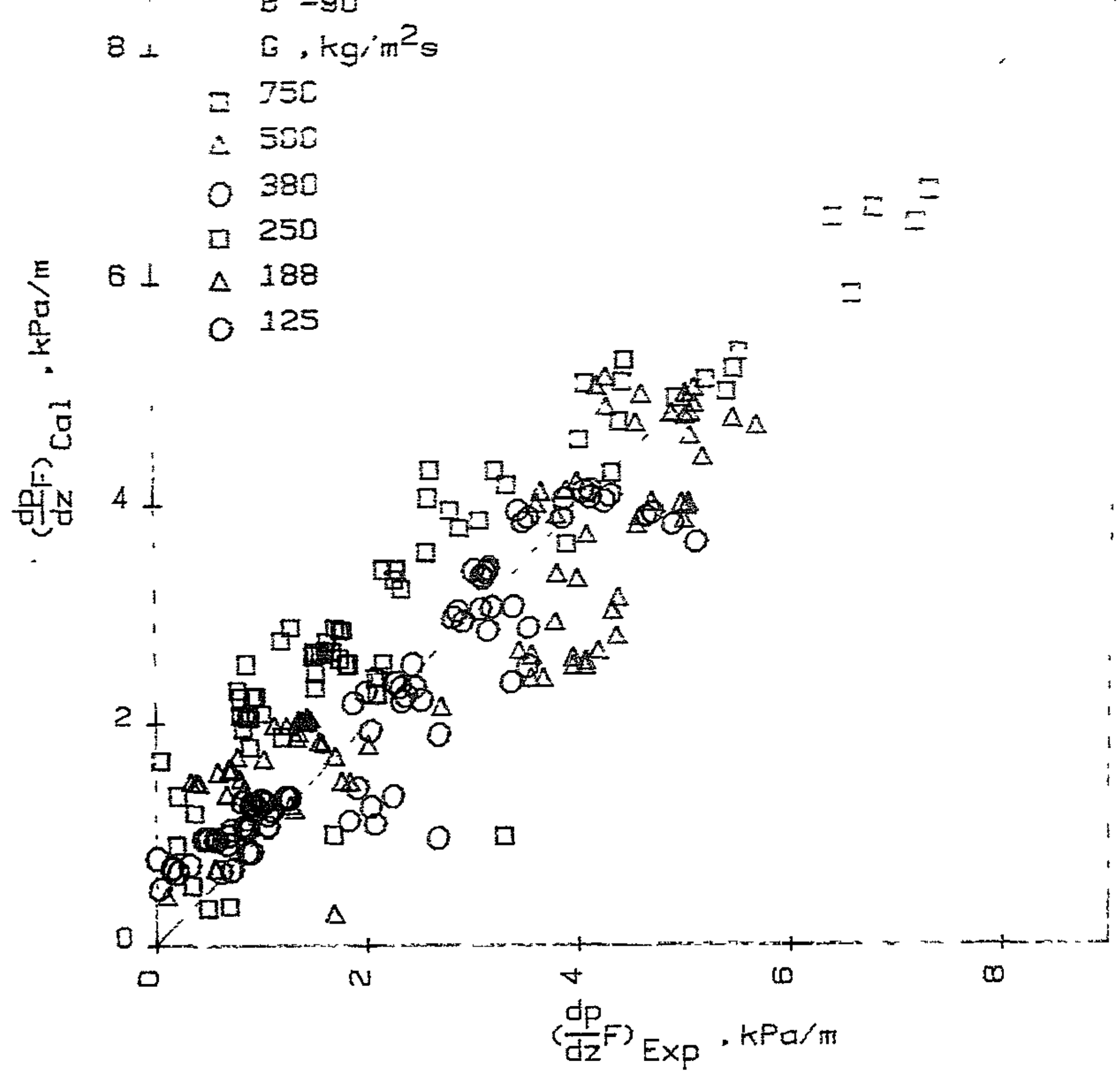


FIG 4.10B Comparison of Frictional Pressure Drop obtained Using the Dengler-Addoms Void Fraction Correlation with that Computed from the Baroczy Correlation

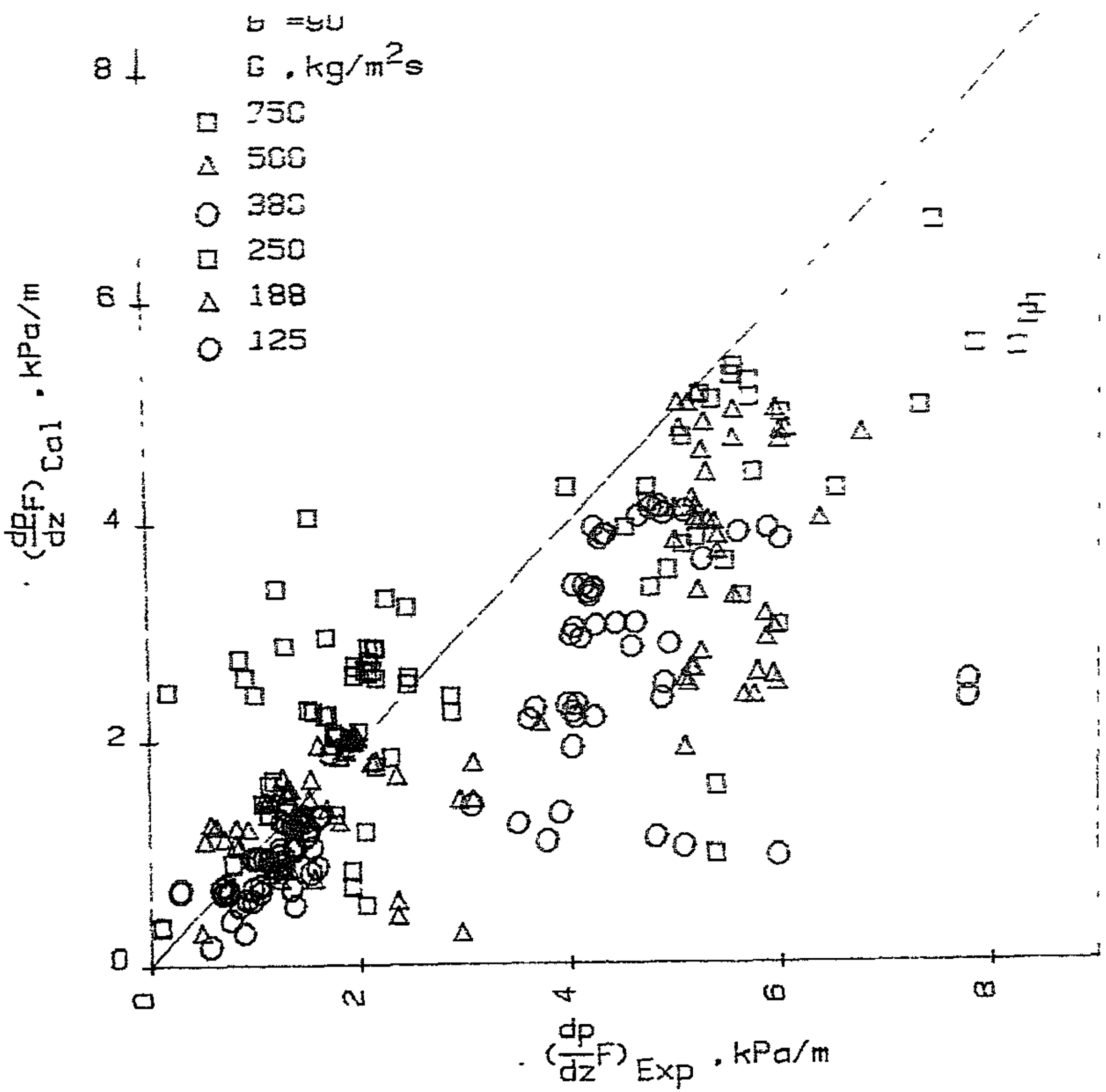


FIG 4.10C Comparison of Frictional Pressure Drop obtained Using the Beggs-Brill Void Fraction Correlation with that Computed from the Baroczy Correlation

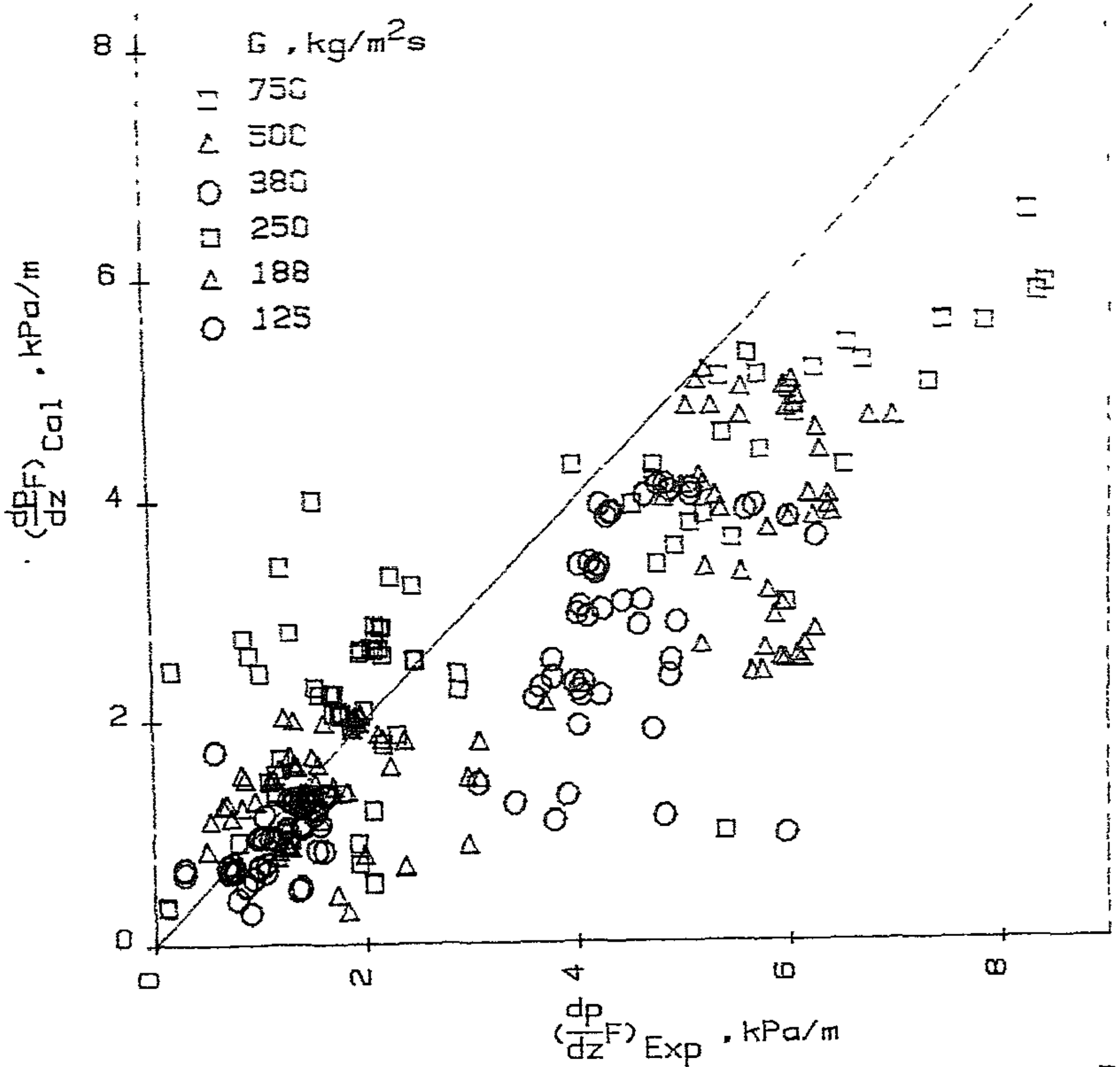


FIG 4.10D Comparison of Frictional Pressure Drop obtained Using the Void Fraction Data of Isbin et al. with that Computed from the Baroczy Correlation

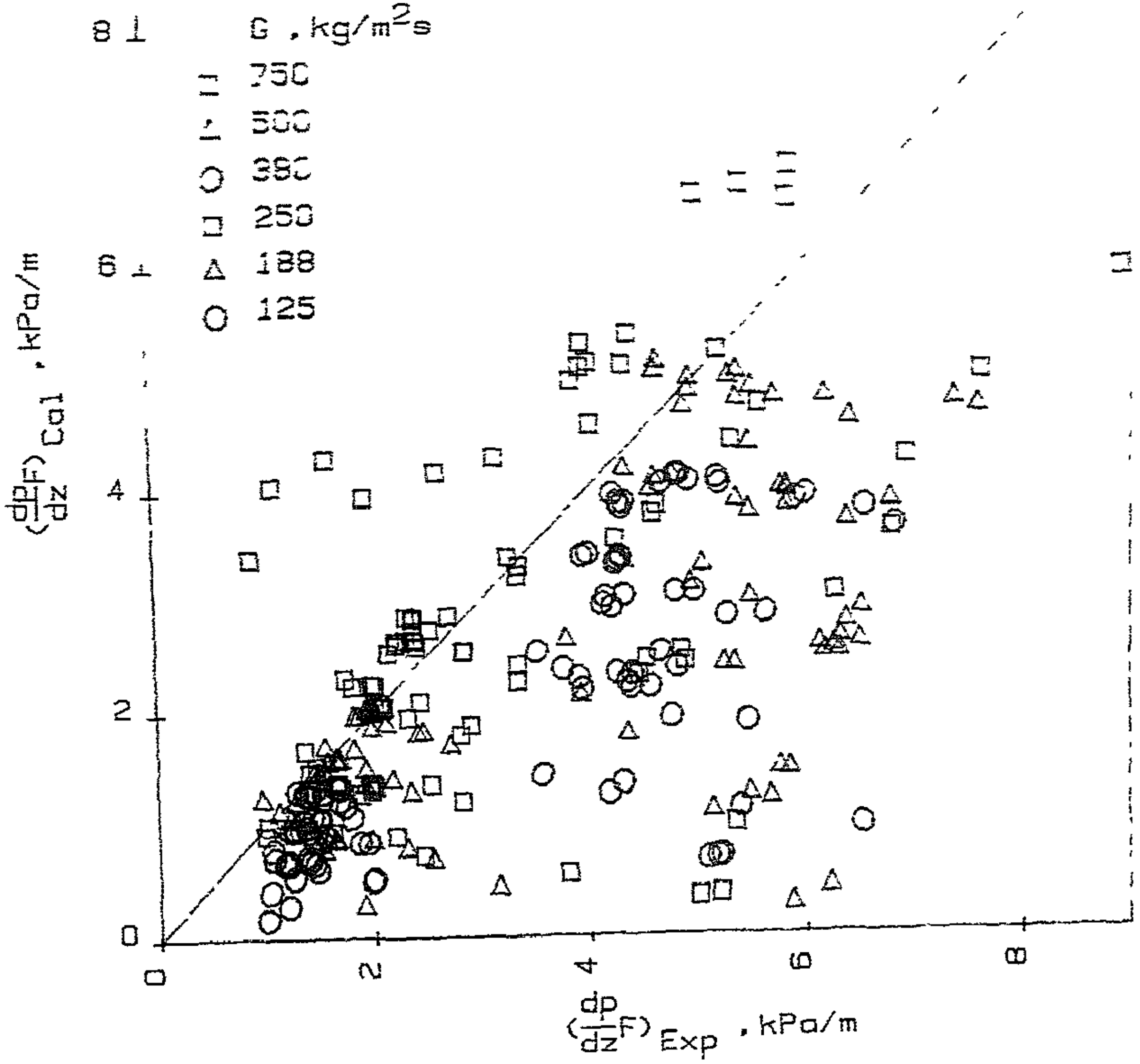


FIG 4.10E Comparison of Frictional Pressure Drop obtained using the Void Fraction Corrl. of Lockhart-Martinelli with the Beggs and Brill Correction factor with that Computed from the Baroczy Corrl.

The literature on void fraction for the two-phase flow in inclined tube is meagre. Beggs and Brill (1973) have measured void fraction for the upward and downward flow at different angles of inclination. They found that the void fraction is a function of angle of inclination. They have suggested correction factors that are to be multiplied with the void fraction in horizontal flow to get the void fraction for the inclined flow and correlated the correction factors in terms of the angle of inclination, Froude number and volumetric quality. Nguyen and Spedding (1977) obtained the data for air water system for various inclinations and observed that their data is not substantiating the Beggs and Brill correlation. They proposed a graphical correlation for the void fraction. Since most of the present data are outside the range of their correlation, it could not be used. In view of lack of reliable correlation for the void fraction in two-phase flow in inclined tubes, the following procedure has been adopted to obtain the void fraction.

Since the Dengler-Addoms correlation seems to be a reliable one for the vertical case the void fraction at any other inclination is obtained by applying the Beggs and Brill correction factor, $\Delta(\theta)$, as given below:

$$(1-\alpha)_{\theta} = (1-\alpha)_{DA} \; \Delta(\theta)/\Delta(90) \qquad 4.13$$

where $(1-\alpha)_{DA}$ is liquid holdup evaluated from Dengler-Addoms correlation. Employing the void fraction thus obtained, the three components of the total pressure drop were evaluated. This method of estimation of void fraction in inclined tubes needs experimental justification; but it could not be done due to lack of data. The total pressure drop with the other relevant experimental parameters are tabulated in Appendix C. From the tabular data it is possible to evaluate the three components of the total pressure drop whenever a more accurate void fraction correlation is available.

4.2.3 Variation of Frictional Pressure Drop with Quality and Angle of Inclination

Figure 4.11A to 4.11C show the variation of frictional pressure drop with quality for different inclinations for $G = 500\ kg/m^2s$. It can be seen that for the angles of inclination 67.5° and 90° two distinct regions were present. In the first region the frictional pressure drop increased with quality whereas in the second it was more or less constant. The flow pattern, where the constant region prevailed was found to be annular while the other region to be slug or bubbly flow.

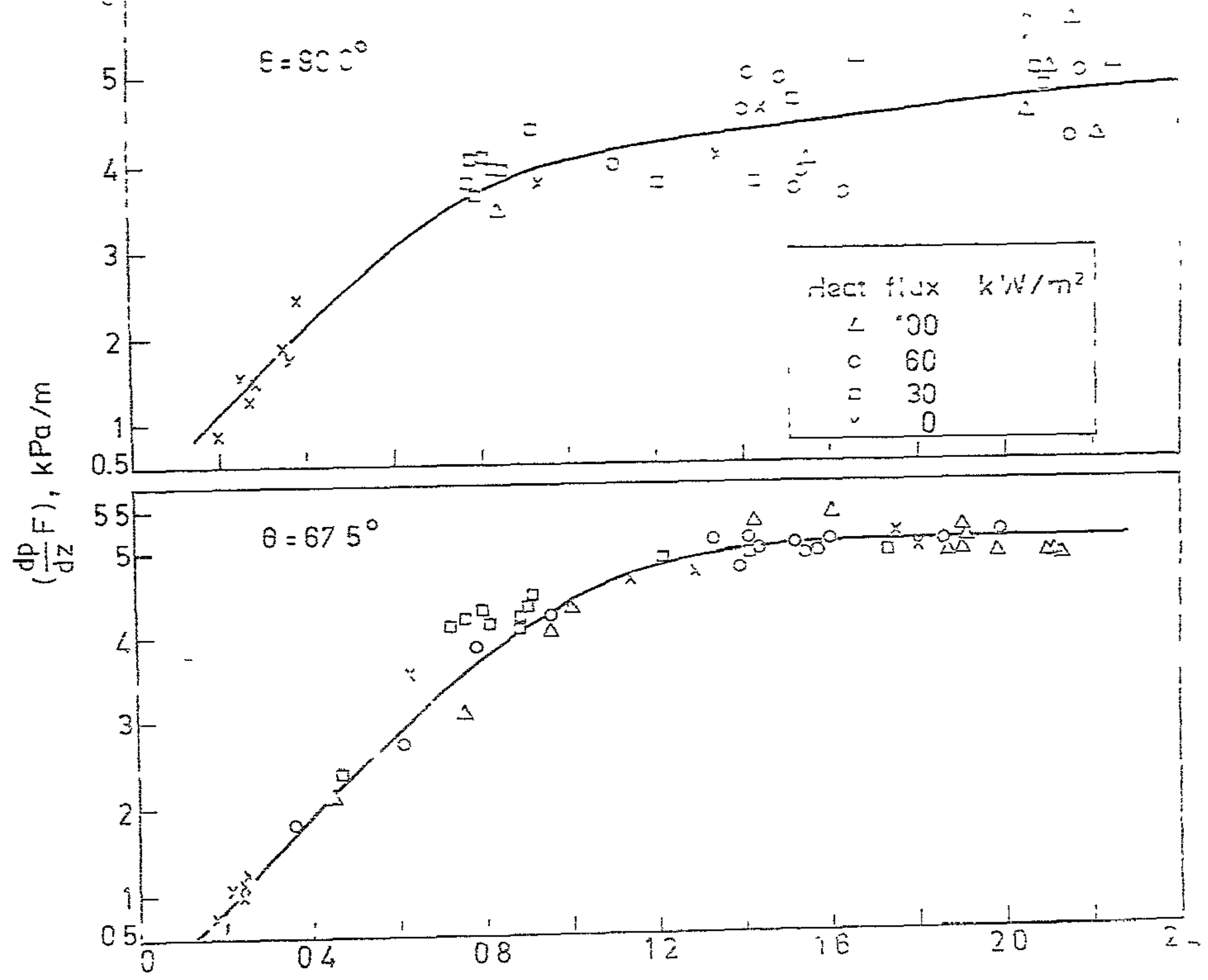


Fig 4.11A Frictional pressure drop versus quality for $G = 500\ kg/m^2s$

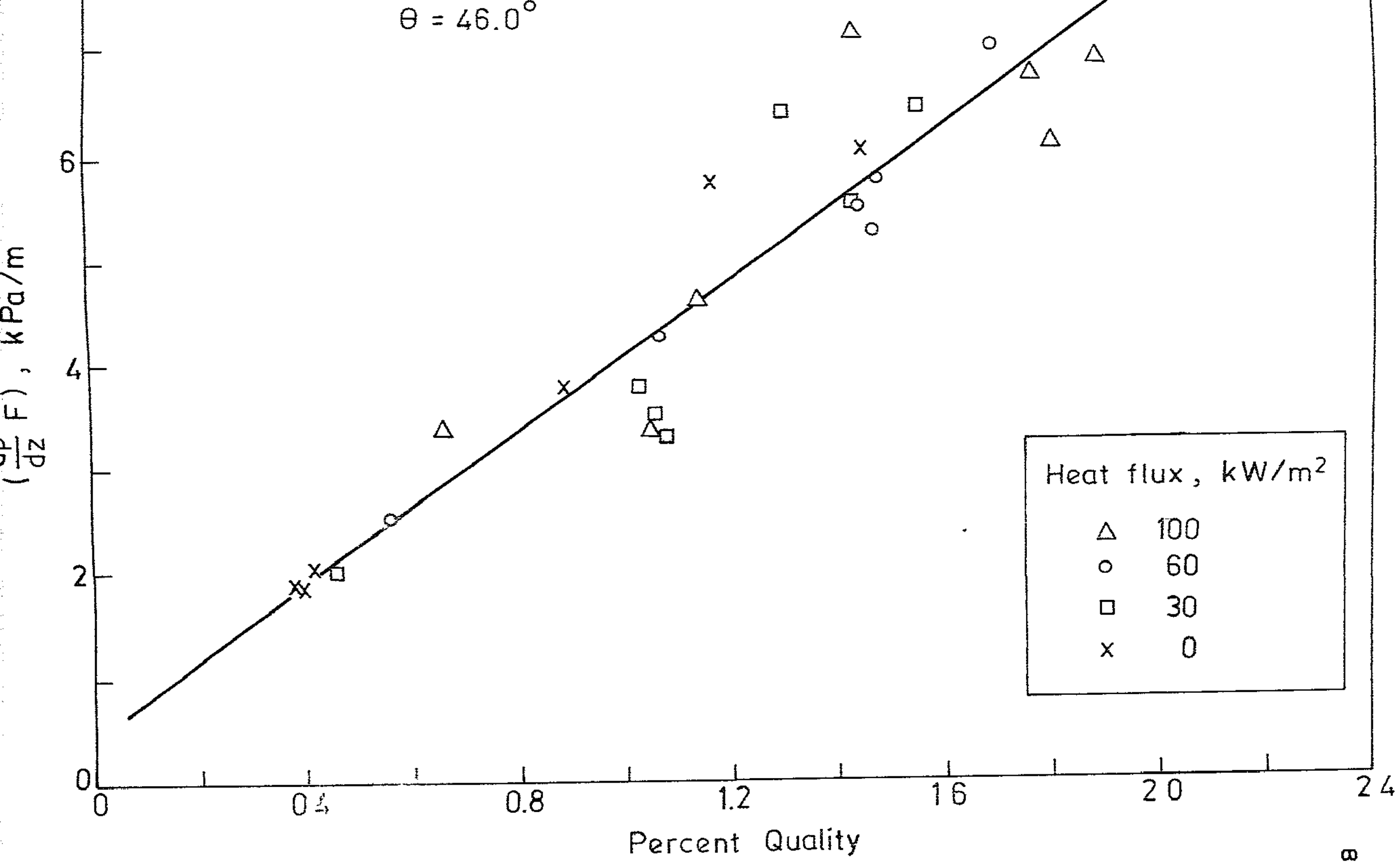


Fig. 4.11B Frictional pressure drop versus quality for $G=500 kg/m^2s$

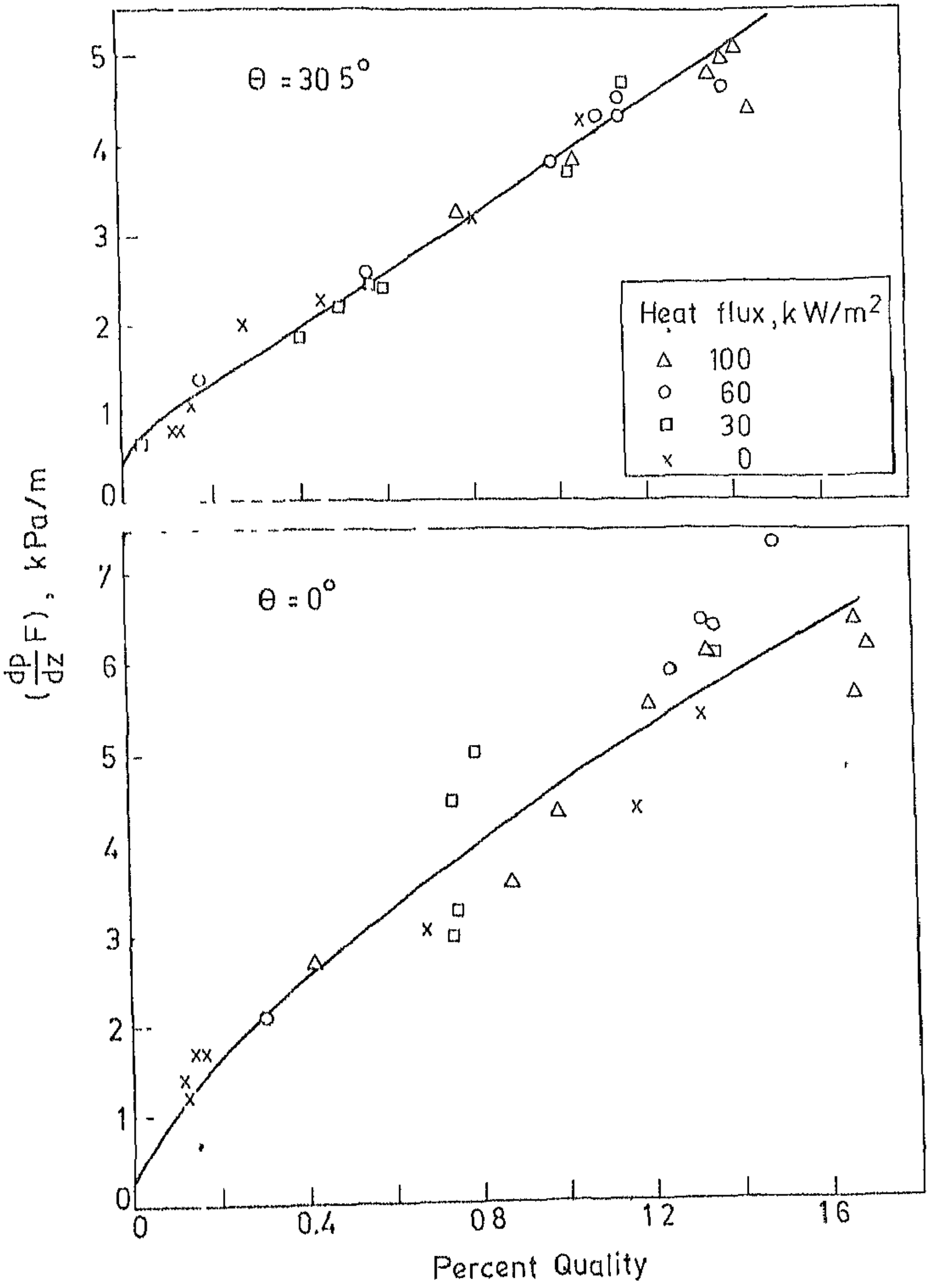


Fig 4 11C Frictional pressure drop versus quality for G=500 kg/m²s

With decrease in inclination the annular flow pattern, where a constant region was observed, shifted to higher qualities. Similar trend was observed for G = 380 kg/m^{2}s. For G = 750 kg/m^{2}s the only region, where the pressure drop increased with quality, was observed for all inclinations. Figure 4.12 shows the frictional pressure drop versus quality for G = 125 kg/m^{2}s. As can be seen there is no significant change of pressure drop with quality. For $\Theta = 90°$, negative pressure drops were observed in the low quality region. Similar trends were observed for G = 250 and 188 kg/m^{2}s. The negative pressure drops were also observed by other investigators (Spedding et al., 1982). These were attributed to buoyancy forces (Spedding and Nguyen, 1978). From Figures 4.11A to 4.11C it can be inferred that heat flux has no effect on the frictional pressure drop. Shoukri et al. (1981) have studied the effect of heat flux on the frictional pressure drop. Their data also indicate that the effect is negligible if quality is less than 8 %.

Typical plots, depicting the effect of Θ on the frictional pressure drop, are shown in Figures 4.13A to 4.13C. The points shown in these plots were obtained from the smooth curves drawn on the plots of the frictional

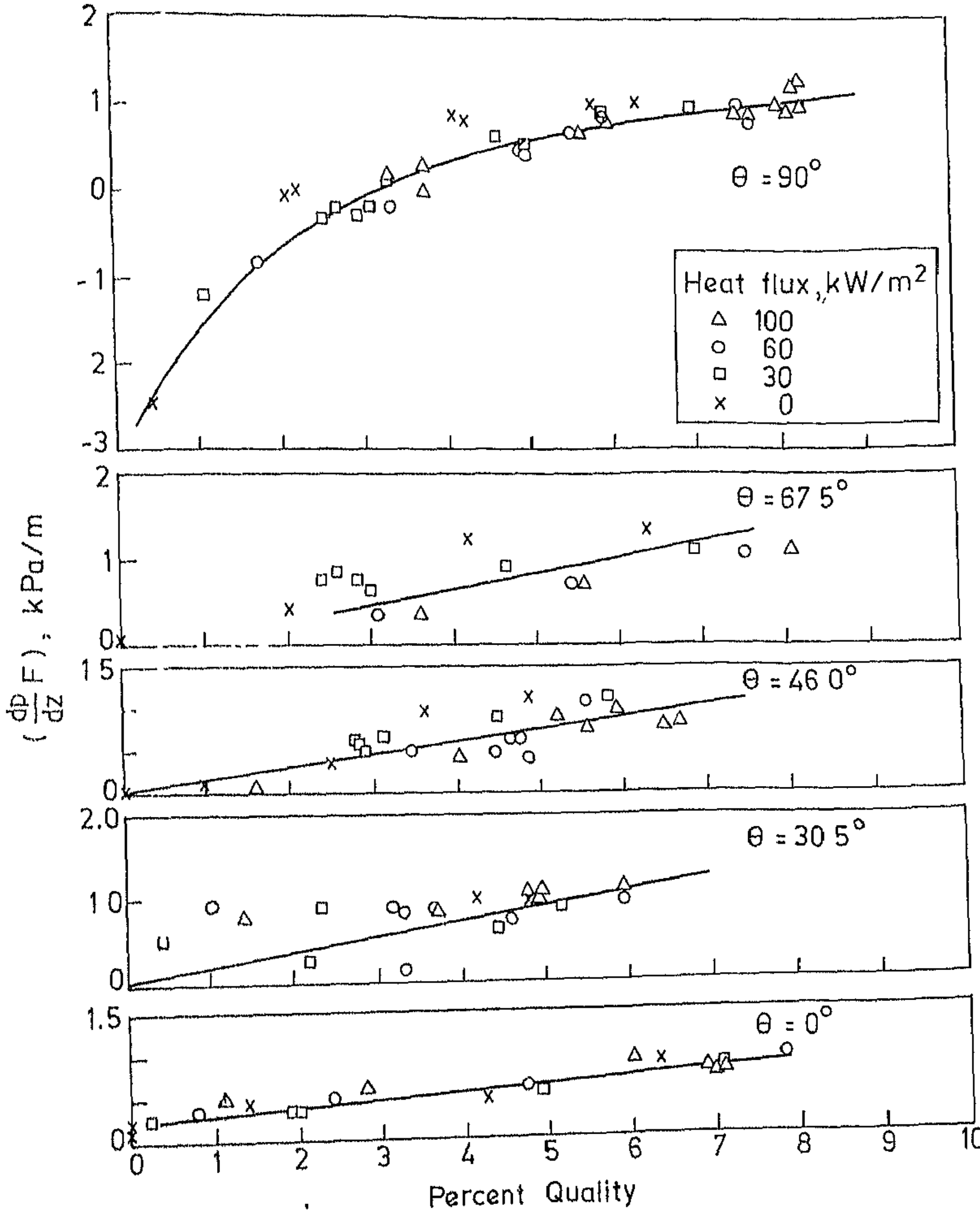


Fig 4.12 Frictional pressure drop versus quality for G = 125 kg/m²s

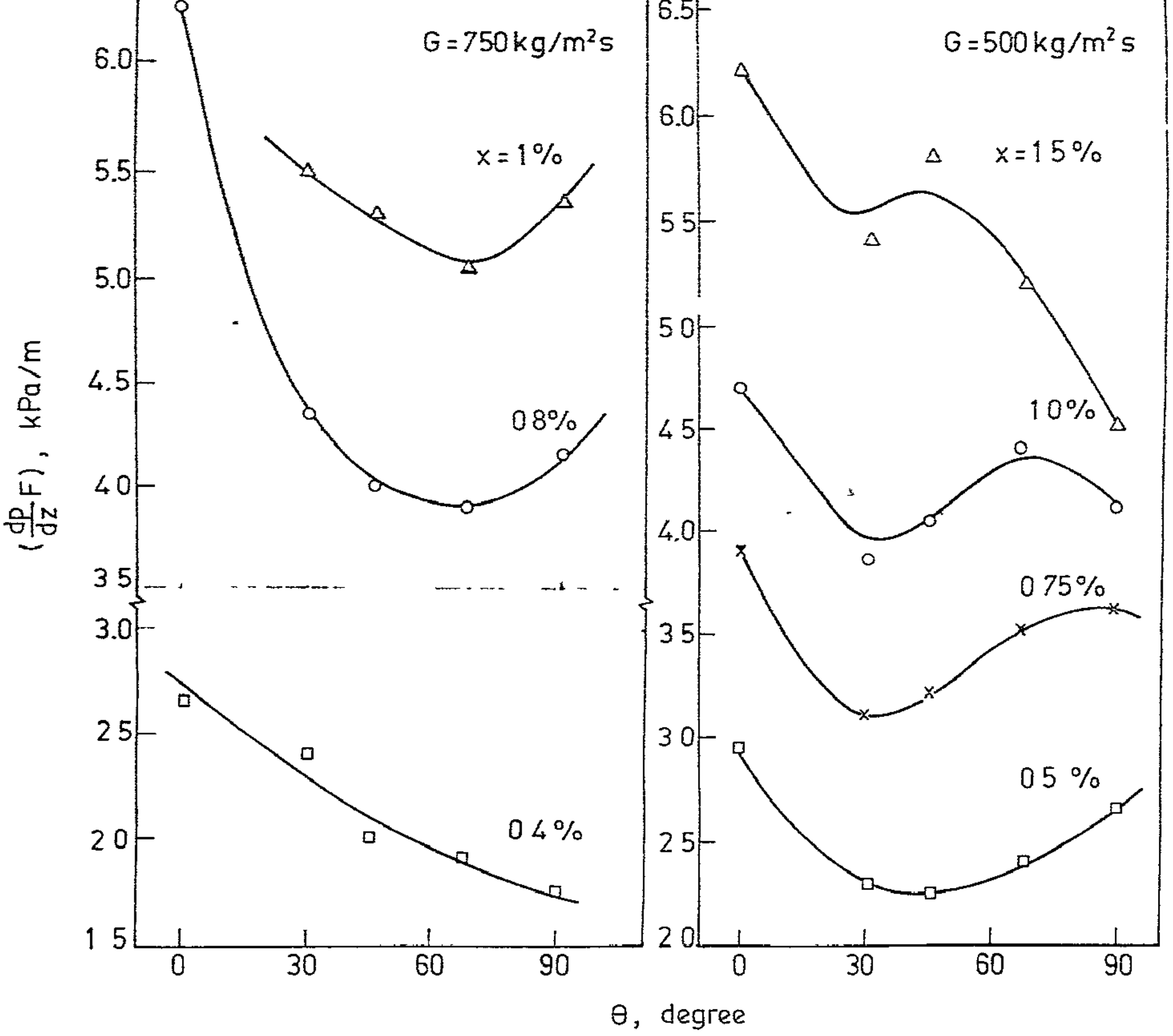


Fig 4 13A Variation of frictional pressure drop with θ.

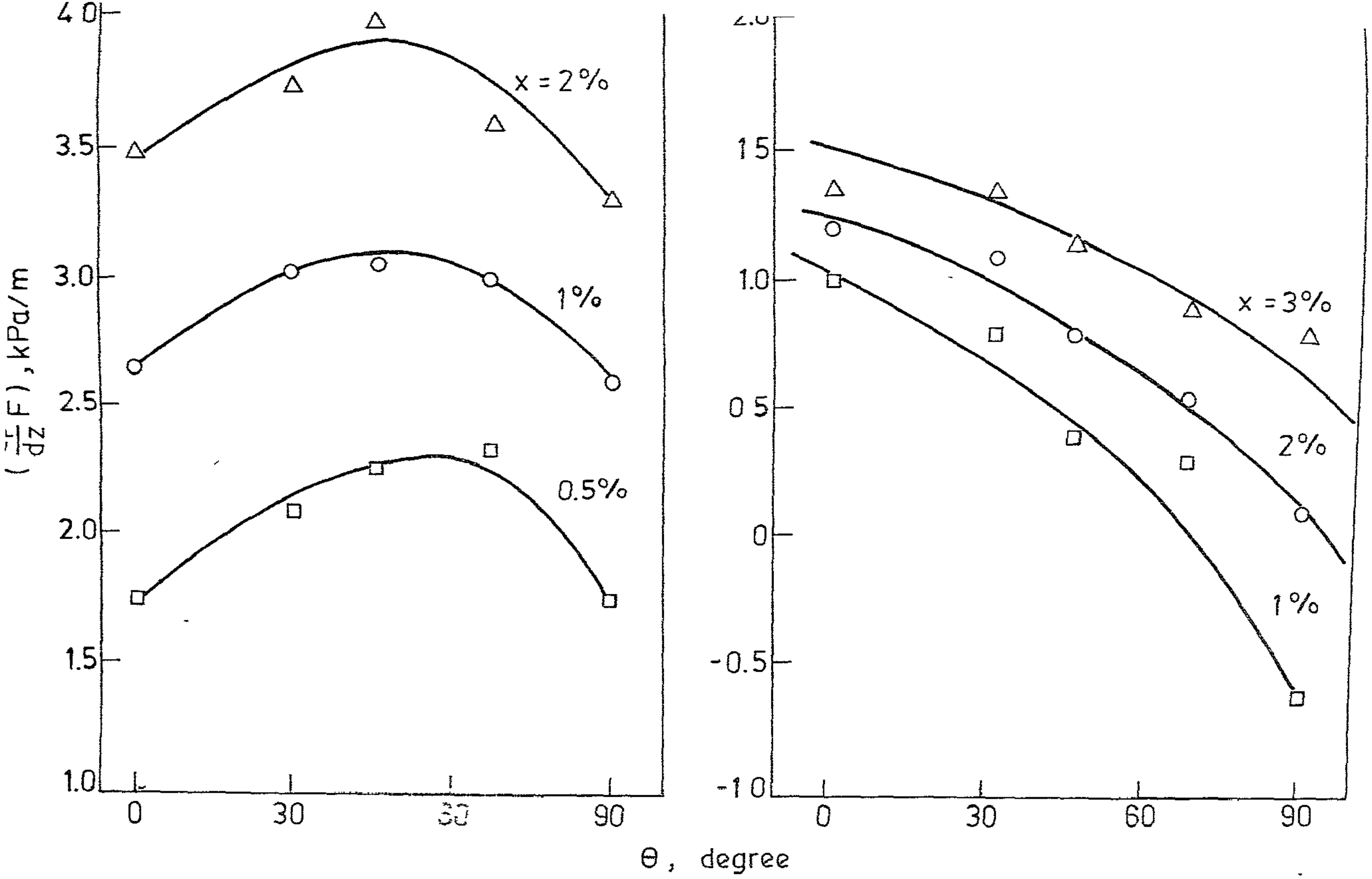


Fig. 4.13B Variation of frictional pressure drop with θ .

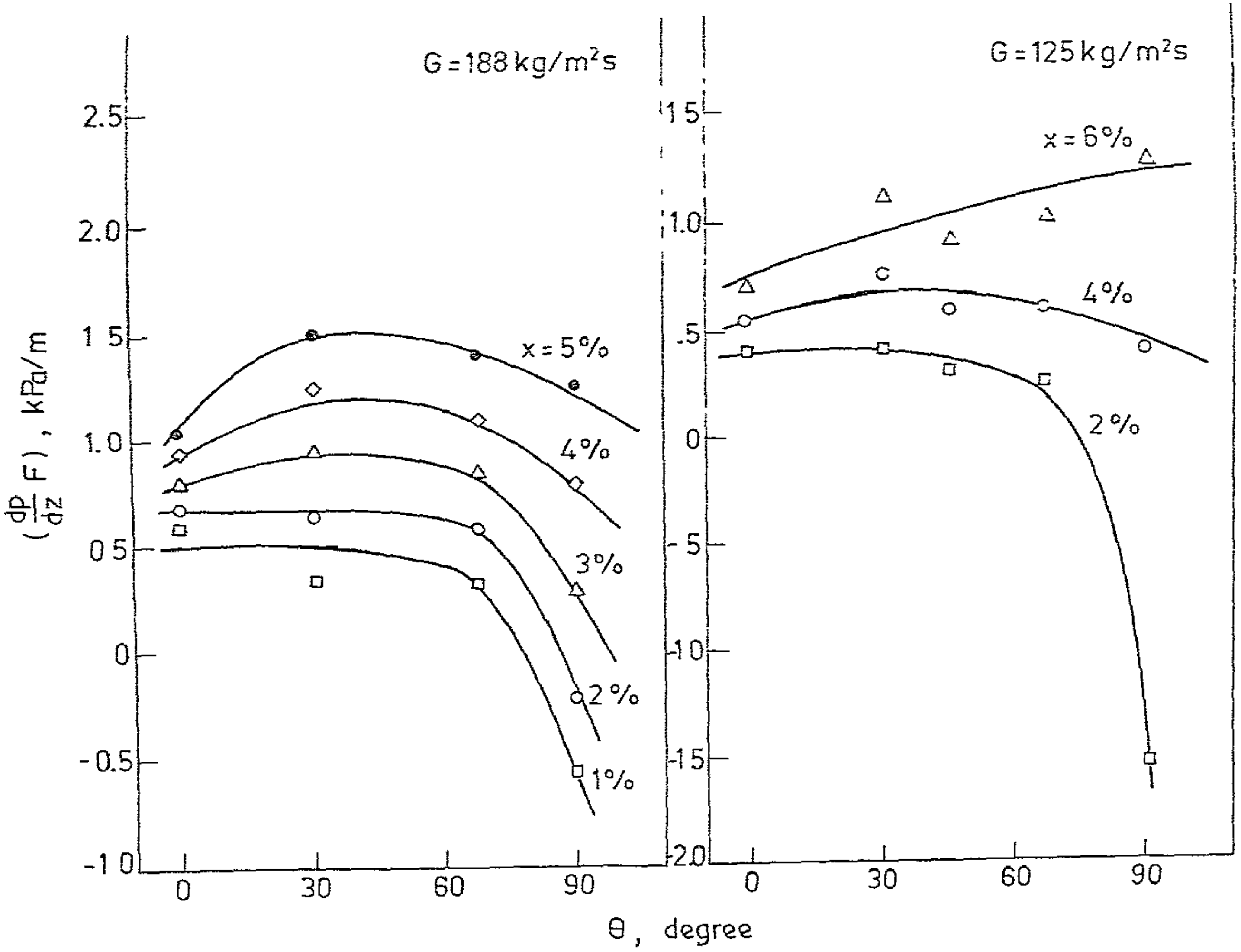


Fig 4.13C Variation of frictional pressure drop with θ

pressure drop versus quality. The effect of angle of inclination on the frictional pressure drop can be seen to depend strongly on mass velocity as well as quality. There appears to be some general trend but it could not be deciphered based on flow patterns. Spedding et al. also observed such behaviour if not very similar. But clear understanding of this behaviour and its effect on heat transfer needs a detailed study of pressure drop, void fraction as well as flow patterns simultaneously.

4.2.4 Comparison of Data with Correlations

The widely used Baroczy's correlation and its modified version proposed by Chisholm (1973) have been shown by Friedel (1976) to be superior to other correlations. But, Collier (1972) recommended that the Chisholm method should be used for the property index greater than 0.01. Since the property index in the present case is about 0.001, the original Baroczy correlation has been selected for comparison for all inclinations. For use on computer, the Baroczy graphical correlation has been converted to an analytical form for property index of 1.37×10^{-3} and is given below:

$$\varphi^2_{fo,G} = \varphi^2_{fo(G=1356)}{}^{-n}$$

$$\varphi'_{fo(G=1356)} = 1.75 + 717.8\,x - 3810.8\,x^2 + 2.1\times10^4 x^3$$

$$\Omega = (\Omega_{10} - \Omega_1)(x-1)/9 + \Omega_1$$

$$\Omega_1 = 1.5519 - 0.3993\times10^{-3}G + 0.30041 \times 10^{-7}G^2$$

for $x = 1\%$

$$\Omega_{10} = 1.796 - 0.875 \times 10^{-3}G + 0.1792 \times 10^{-6}G^2 \qquad 4.14$$

for $x = 10\%$

where $\varphi^2_{fo,G}$ = two-phase frictional multiplier based on pressure gradient for total flow assumed liquid at mass velocity, G,

and Ω = mass velocity correction factor.

Strictly speaking, these equations are valid for $4048 < G < 340$ kg/m^{2}s. Nonetheless, these equations were also used even for G = 125 to 250 kg/m^{2}s. The frictional pressure drop across the pre-evaporator E3, was estimated from the equation

$$\frac{\Delta pF}{(\Delta pF)_{fo}} = \frac{1}{(x_o - x_i)} \int_{x_i}^{x_o} \varphi^2_{fo(G=1356)}\,\Omega\,dx$$

$$\simeq \frac{\Omega}{(x_o - x_i)} \int_{x_i}^{x_o} \varphi^2_{fo(G=1356)}\,dx \qquad 4.15$$

The comparison of the experimental and estimated ΔPF are shown in Figures 4.14A to 4.14E for various inclinations and the average and mean errors are given

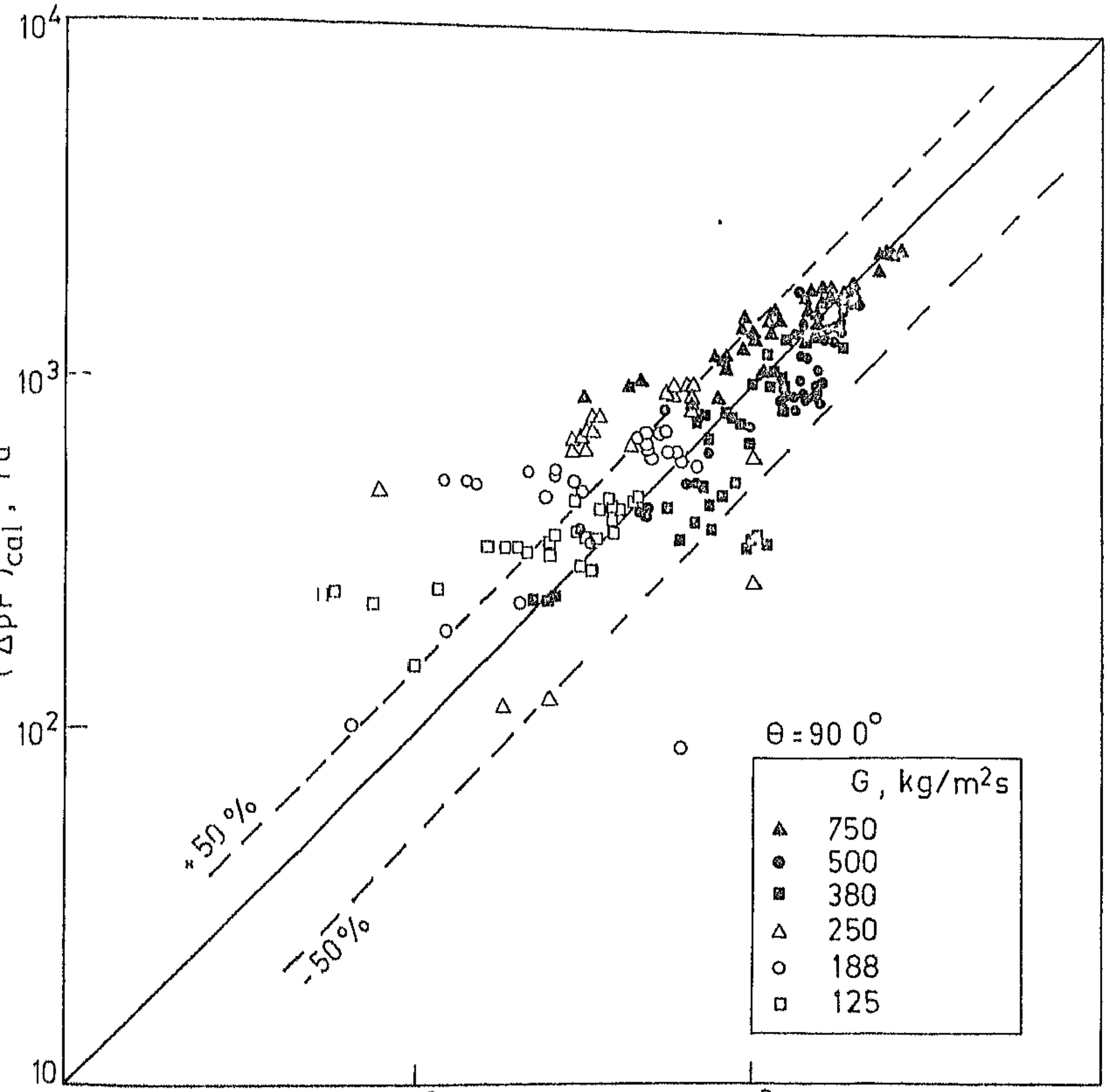


Fig 4 14A Comparison of frictional pressure drop with the Baroczy correlation for θ = 90°.

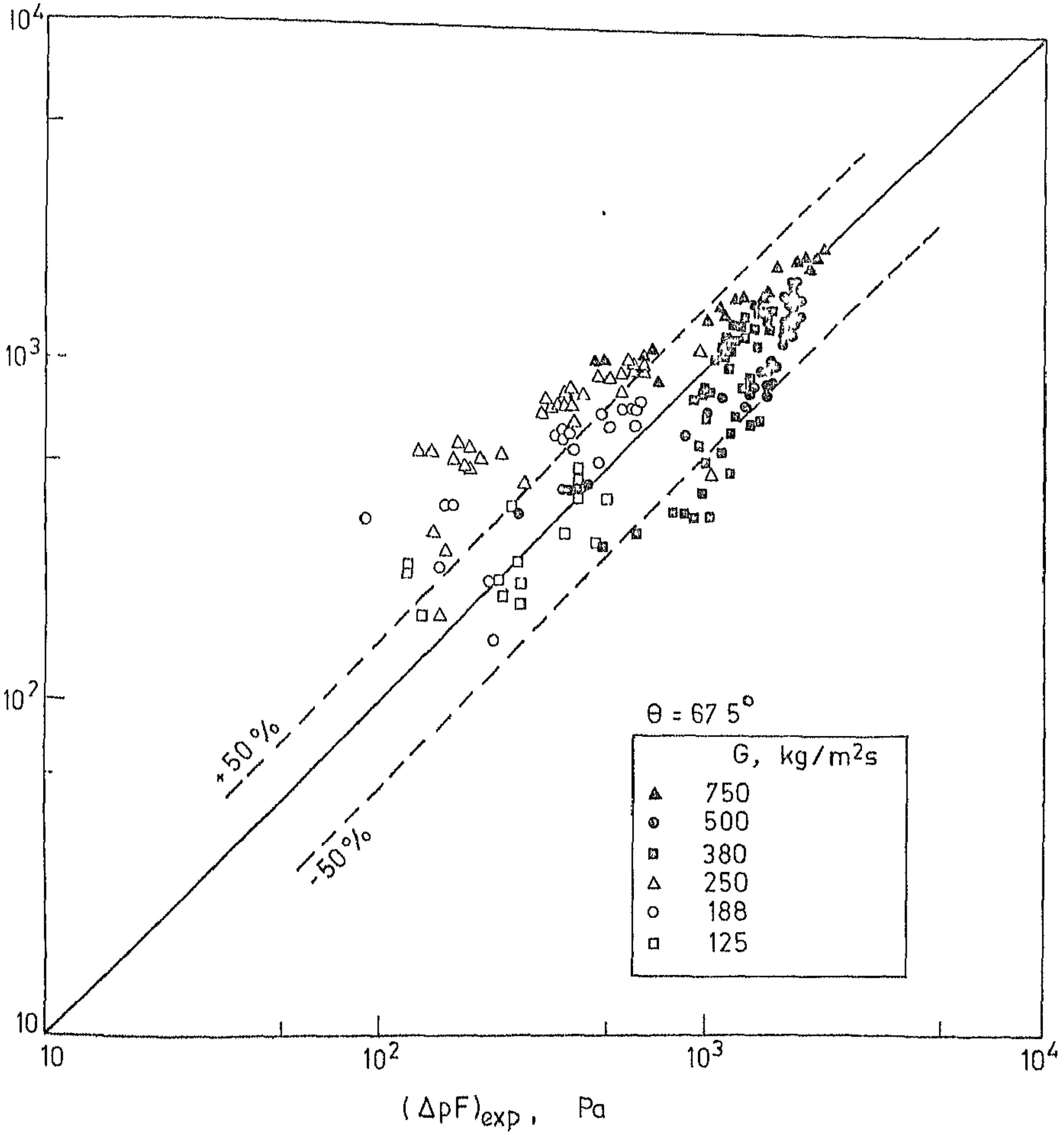
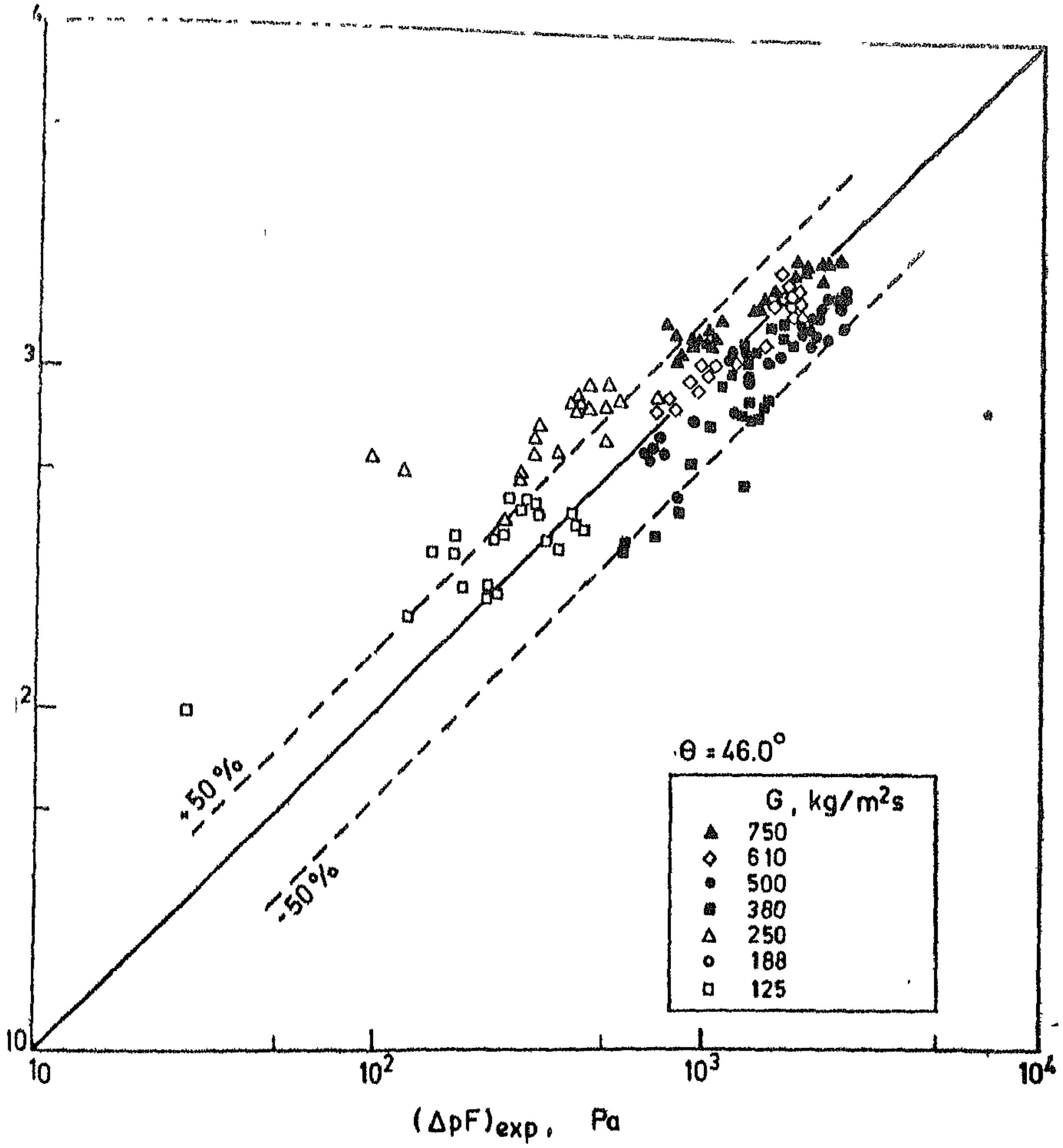
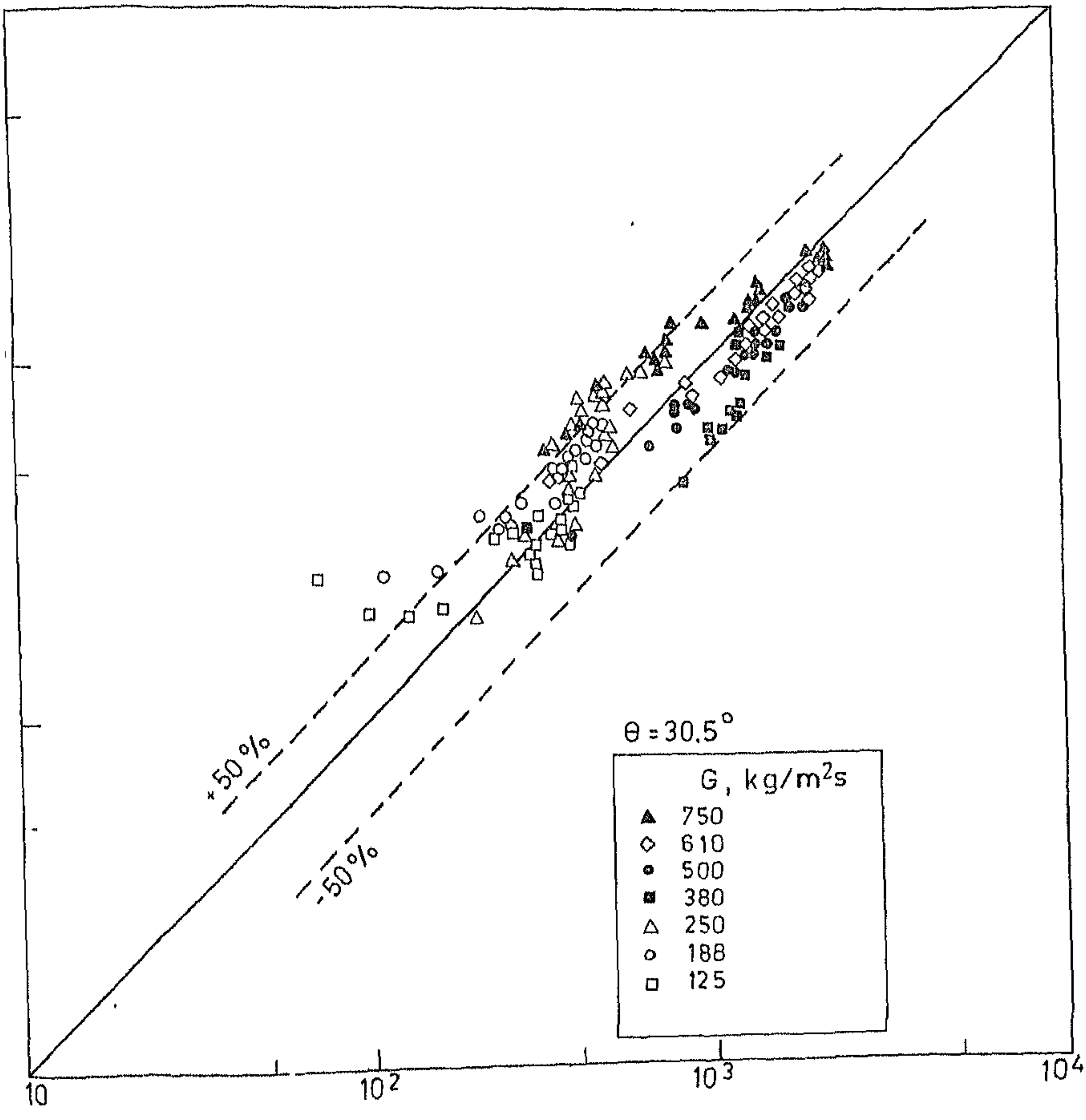


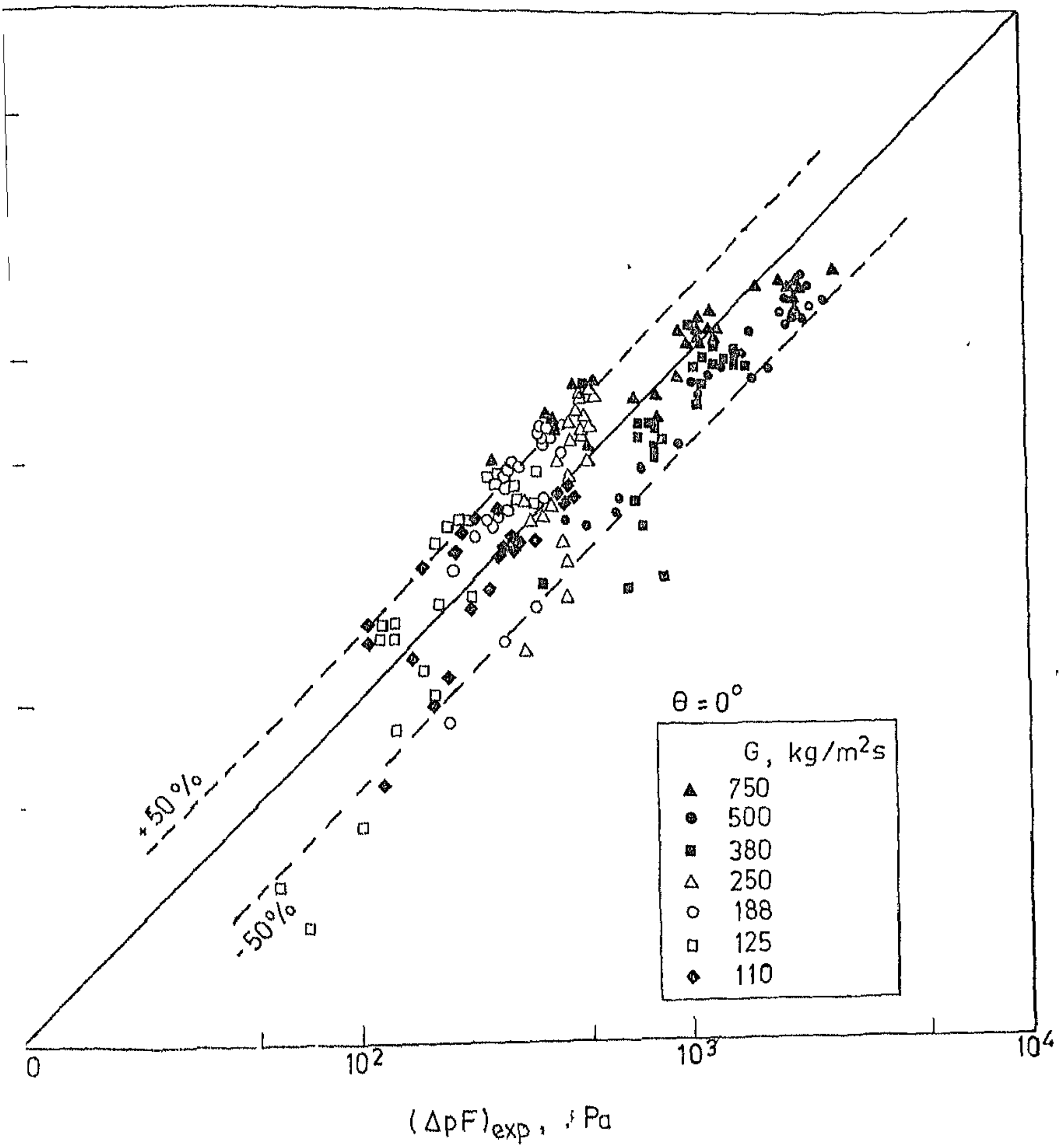
Fig 4 14 B Comparison of frictional pressure drop with the Baroczy correlation for θ = 67 5°



ig.4.14C Comparison of frictional pressure drop with the Baroczy correlation for θ = 46.0°.



ig 4.14D Comparison of frictional pressure drop with the Baroczy correlation for θ = 30.5°.



4.14E Comparison of frictional pressure drop with the Baroczy correlation for $\Theta = 0^\circ$.

in Table 4.4. It can be seen that the agreement is better at higher flow rates (filled symbols) than at lower flow rates. The agreement is also better at smaller angles of inclination. At higher angles of inclination and lower qualities, the gravitational component is dominant. Since the frictional component is obtained by subtracting the gravitational component from the total pressure drop, the errors in void fraction are reflected in frictional pressure drop. These errors are large whenever the gravitational component is the dominant one. In addition to this negative pressure drops were observed at the inclinations close to vertical due to buoyancy effects. This may also have contributed to the spread of the data that was observed at 90° and 67.5° of inclination.

From the plots and the table (see standard deviation) it can be seen that the data are deviating systematically with inclination from Baroczy's correlation. It may be possible to get a better correlation by modifying the Baroczy correlation for inclined cases. In view of the uncertainity in void fraction, no attempt has been made in this direction. Considering the fact that the overall data are within ± 50 % error bounds and the average error is within 30 % irrespective of inclination

TABLE 4.5

AVERAGE, MEAN AND STANDARD DEVIATIONS OF THE PRESSURE DROP DATA FROM THE BAROCZY CORRELATION

Degrees	Percent Deviation Average	 Mean	Standard deviation
90.0	30	- 15	5.38
67.5	30	- 5	4.74
46.0	28	- 6	1.09
30.5	30	- 18	0.50
0.0	39	- 17	0.42

$$\text{Percent Average Deviation} = \frac{\sum_{1}^{N} \left| \left(\frac{\text{Exp-Cal}}{\text{Exp}} \right) \right| \times 100}{N}$$

$$\text{Percent Mean Deviation} = \frac{\sum_{1}^{N} \left(\frac{\text{Exp-Cal}}{\text{Exp}} \right) \times 100}{N}$$

$$\text{Standard Deviation} = \sqrt{\frac{\sum_{1}^{N} \left\{ \frac{\text{Exp-Cal}}{\text{Exp}} - \left[\sum_{1}^{N} \frac{\text{Exp-Cal}}{\text{Exp}} \right] / N \right\}^{2}}{N-1}}$$

(excepting 0°), it may be said that Baroczy's correlation is representing the data reasonably well.

4.2.5 Two-phase Frictional Multiplier

The frictional pressure drop data were also correlated by the Lockhart-Martinelli method. Martinelli-Nelson (1948) expressed frictional pressure drop in terms of two-phase frictional multipliers for the conditions of boiling in which quality changes continuously along the length of the tube, as

$$\left(\frac{\Delta p_F}{\Delta p_F}\right)_{fo} = \frac{1}{(x_o - x_i)} \int_{x_i}^{x_o} (1-x)^{1.75} \, \varphi_f^2 \, dx \qquad 4.16$$

The φ_f^2 was evaluated at the average quality from Equation 4.16 assuming it be constant as the change is small. Considering that

$$\varphi_f^2 = \varphi \left[X_{tt}, G, \theta \right] \qquad 4.17$$

The following correlation was obtained using the multiple exponent regression analysis

$$\varphi_f^2 = 1 + 37.06 / \left[X_{tt}^{0.63} \; G^{0.106} \left(1 + \frac{\cos\,(80+2\theta)}{2}\right)^{0.237} \right] \qquad 4.18$$

The correlation coefficient was 0.88.

The present correlation was compared with the frictional pressure drop data in Figure 4.15. The average and mean percent deviation are 26.8 and -8.0 respectively. It may be recalled that average and mean percent deviations from the Baroczy's correlation are 31.5 and 13.5, respectively. Equation 4.18 shows that the frictional pressure drop depends on mass velocity to the power of 1.65. The power was found to be more or less independent of the angle of inclination. In contrast to this, Lombardi et al. (1972) reported the power to be between 1.4 to 1.6, and Friedel(1977) reported it to be 1.46 for the vertical steam-water flow; while Shoukri et al. (1981) indicated it to be 1.4 for horizontal flow. On the other hand Steiner and Schlunder (1976) reported the power to vary between 1.5 and 1.8 for two-phase flow of nitrogen. The close agreement of the exponent observed in this work with the others may be considered to validate the method adopted for estimation of void fraction in this work. The frictional multipliers are compared with the correlation of Shoukri et al. in Figure 4.16. The agreement is good at low mass velocities where annular flow was prevalent.

4.3 FLOW PATTERN MAPS

Heat, mass and momentum transfer in two-phase flow are known to depend on flow patterns. Hsu and

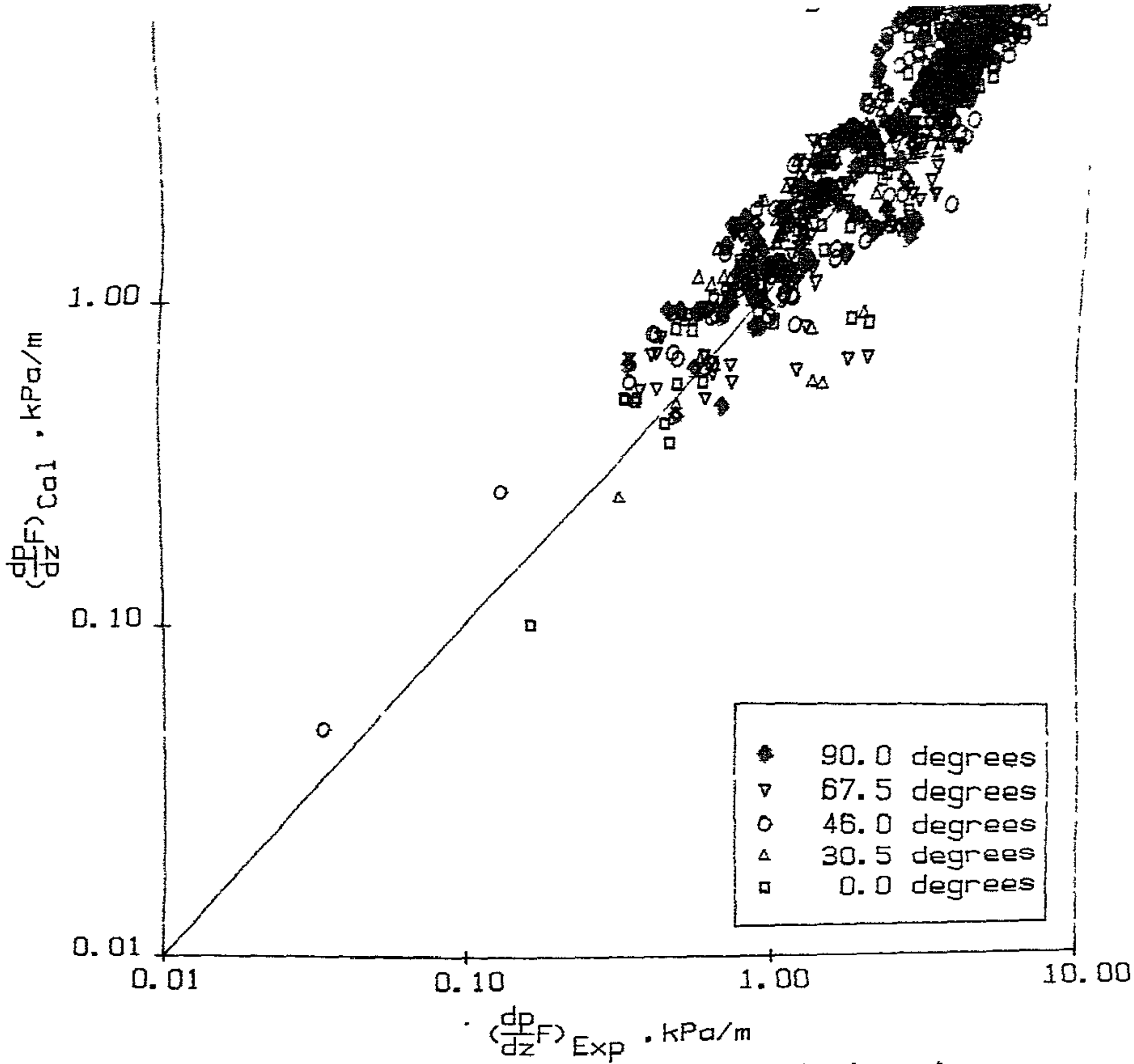


FIG 4.15 Comparison of the Proposed Correlation with the Frictional Pressure Drop Data

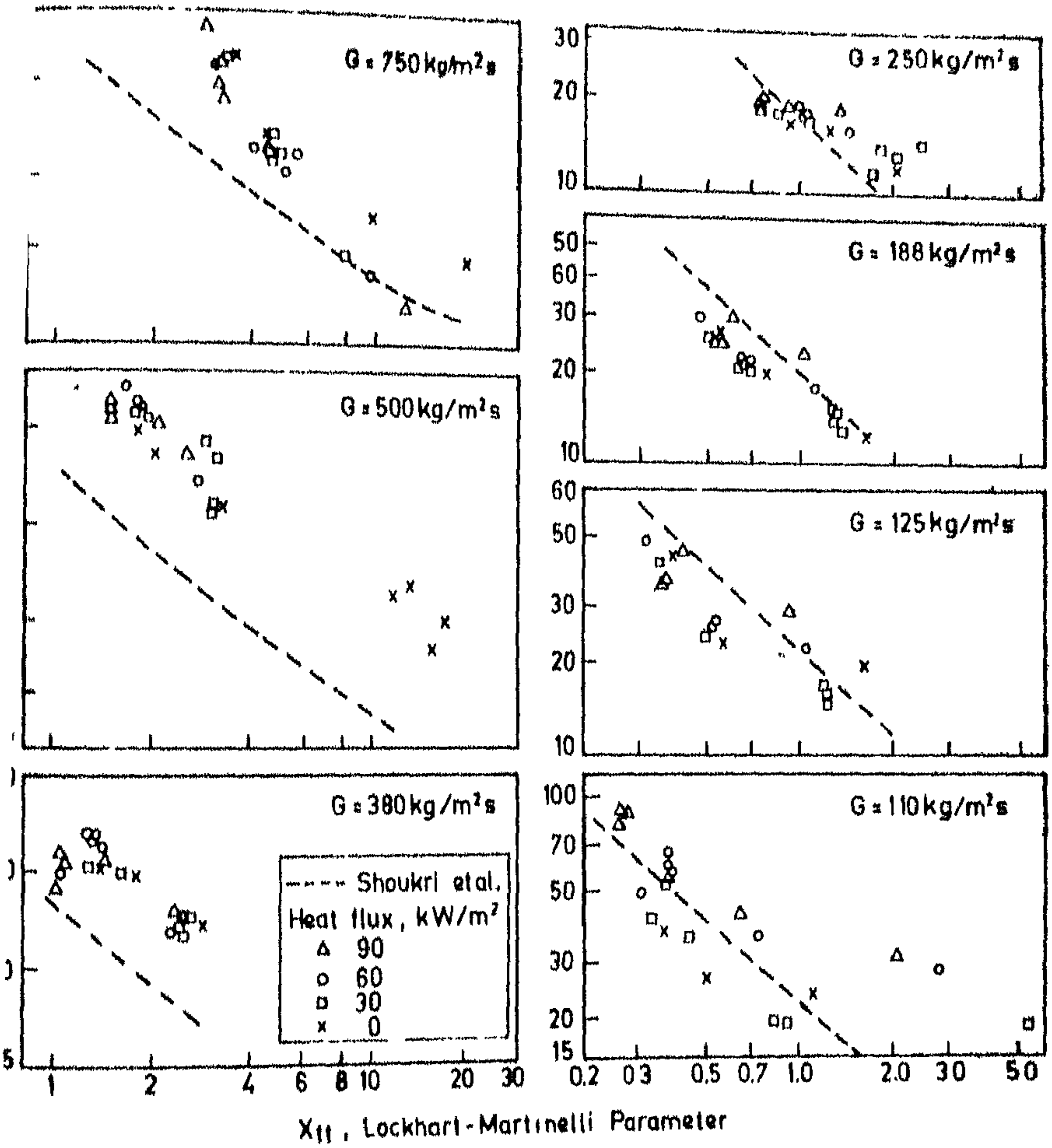


Fig. 4.16 Comparison of the pressure drop data with the correlation of Shoukri et al

Graham (1976) and recently Weisman (1983) have summarised the status of the field. Most of the literature deals with the flow patterns either in horizontal or vertical flows. Only recently the studies have been reported on flow patterns in inclined flow (Spedding and Nguyen,1980; Weisman and Kang,1981; Barnea et al.,1980). The flow patterns in flow boiling could be different from the adiabatic case (Hsu and Graham, 1976) and the data for inclined flow boiling are not available. In this section the flow pattern data are presented which were observed in the glass section (T) (see Figure 3.1). At the outset it may be pointed that no attempt was made to cover all the transition ranges, rather, the flow patterns observed during the heat transfer runs are reported.

For simplicity, the flow pattern is classified as annular, intermittent, separated, bubbly and dispersed. These were distinguished from each other as described below:

Annular Flow: In this pattern continuous liquid film was present on the wall with vapor core and the flow was steady and smooth. At high liquid velocities bubbles were also seen in the liquid film. In horizontal and inclined cases more bubbles were seen in the film at the top than at the bottom side.

Intermittent Flow: In this flow, the collapsed bubbles rather than slugs of vapor were seen. This includes the 'churn' flow referred in the literature.

Separated Flow: This includes separated wavy flow. In this pattern flow of liquid was observed at the bottom side and vapor at the top side with either plane or wavy interface.

Bubbly Flow: The vapor phase was seen distributed as discrete bubbles in a continuous liquid phase. In vertical flow bubbles were seen distributed more or less uniformly across the cross section. In the other cases asymmetric distribution with more bubbles on the top side were seen.

The flow pattern maps are shown in Figures 4.17A to 4.17E on the plots with V_{sg} and V_{sl} as coordinates for all inclinations. The transition lines, which are shown, were obtained from the generalised maps proposed by Weisman and coworkers (1979, 1981). It can be seen from the plots that most of the observed patterns were either annular or intermittent with a few points corresponding to

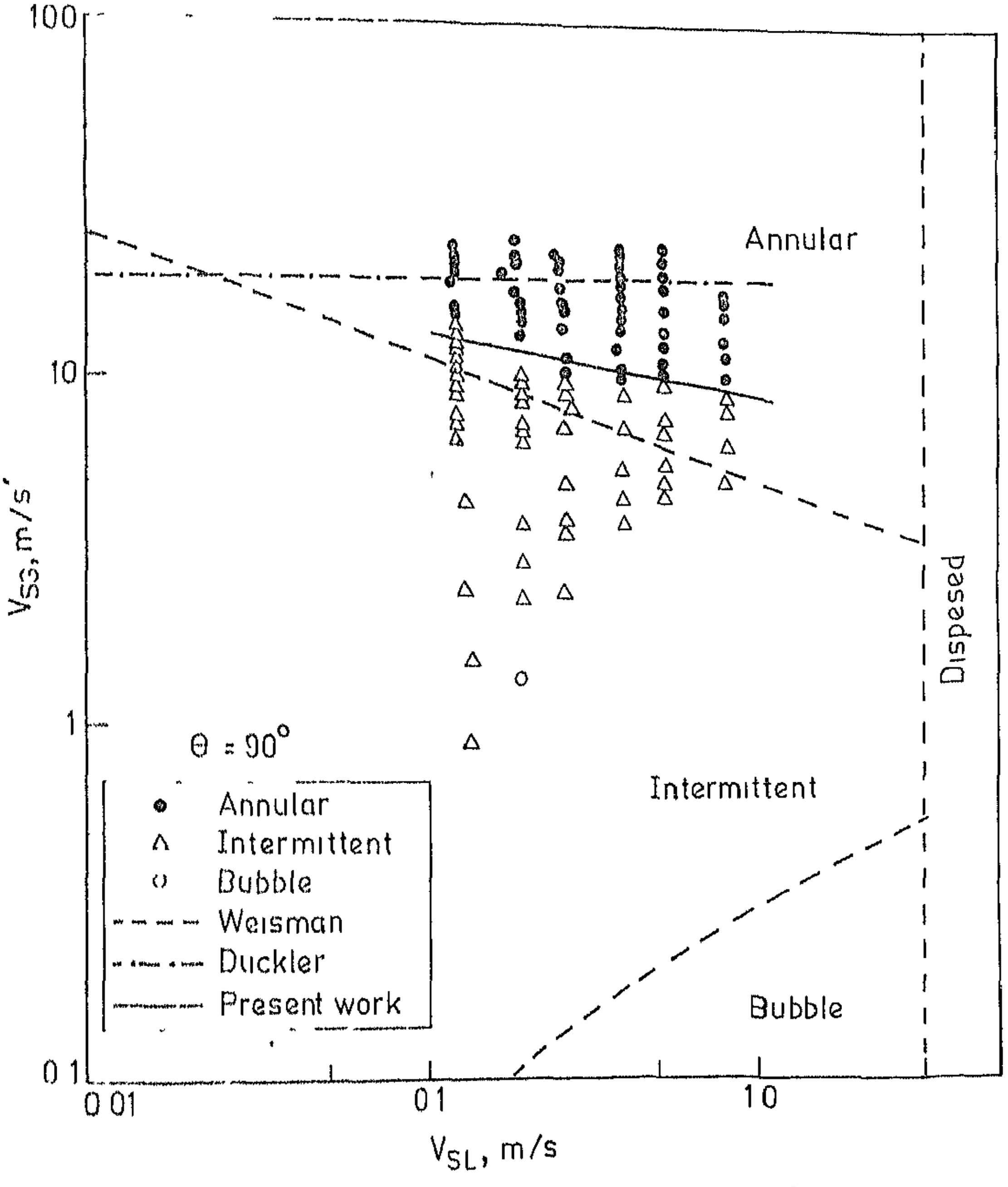


Fig. 4.17A Flow pattern map for θ = 90°

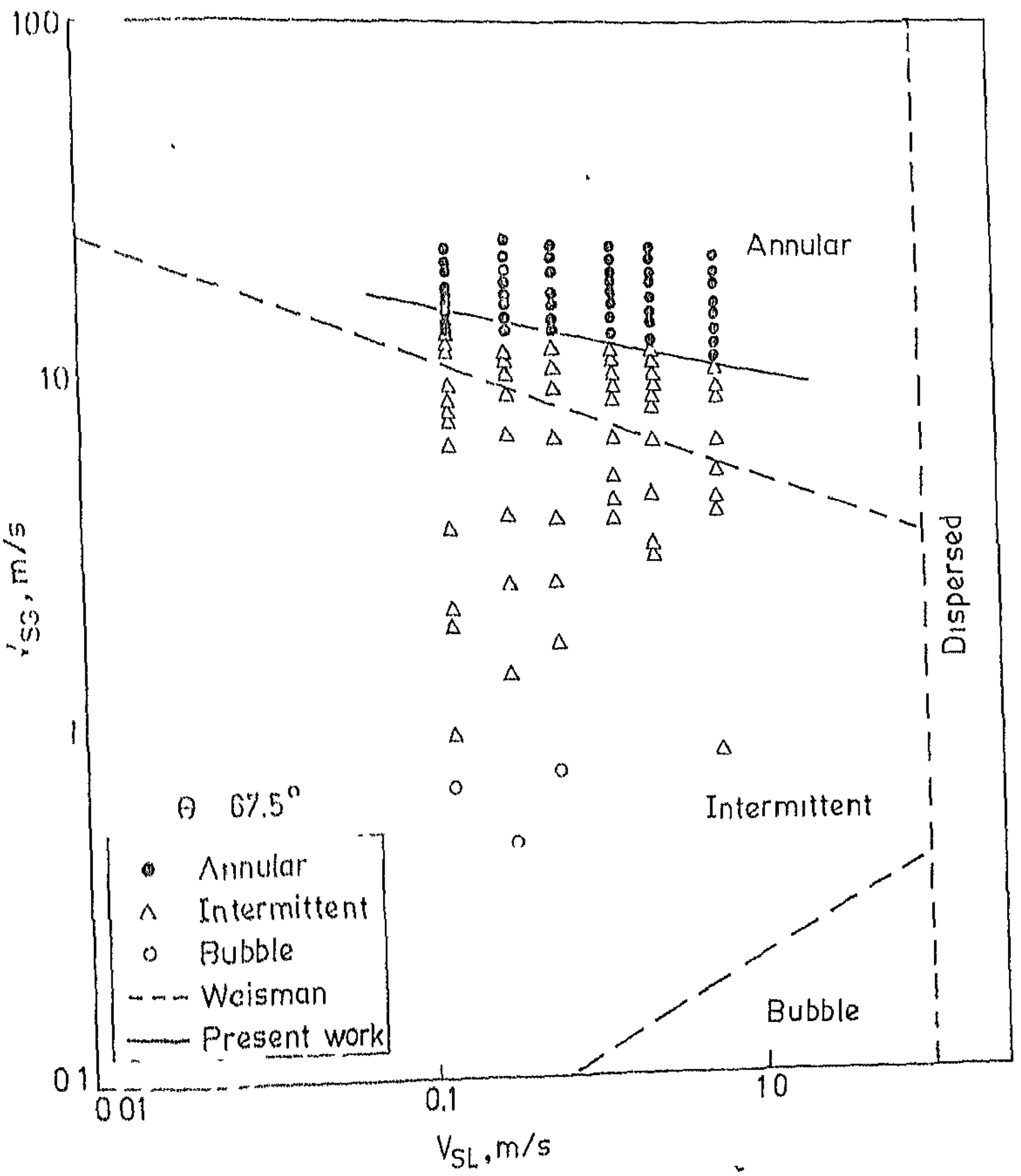


Fig 4.17B Flow pattern map for θ = 67.5°

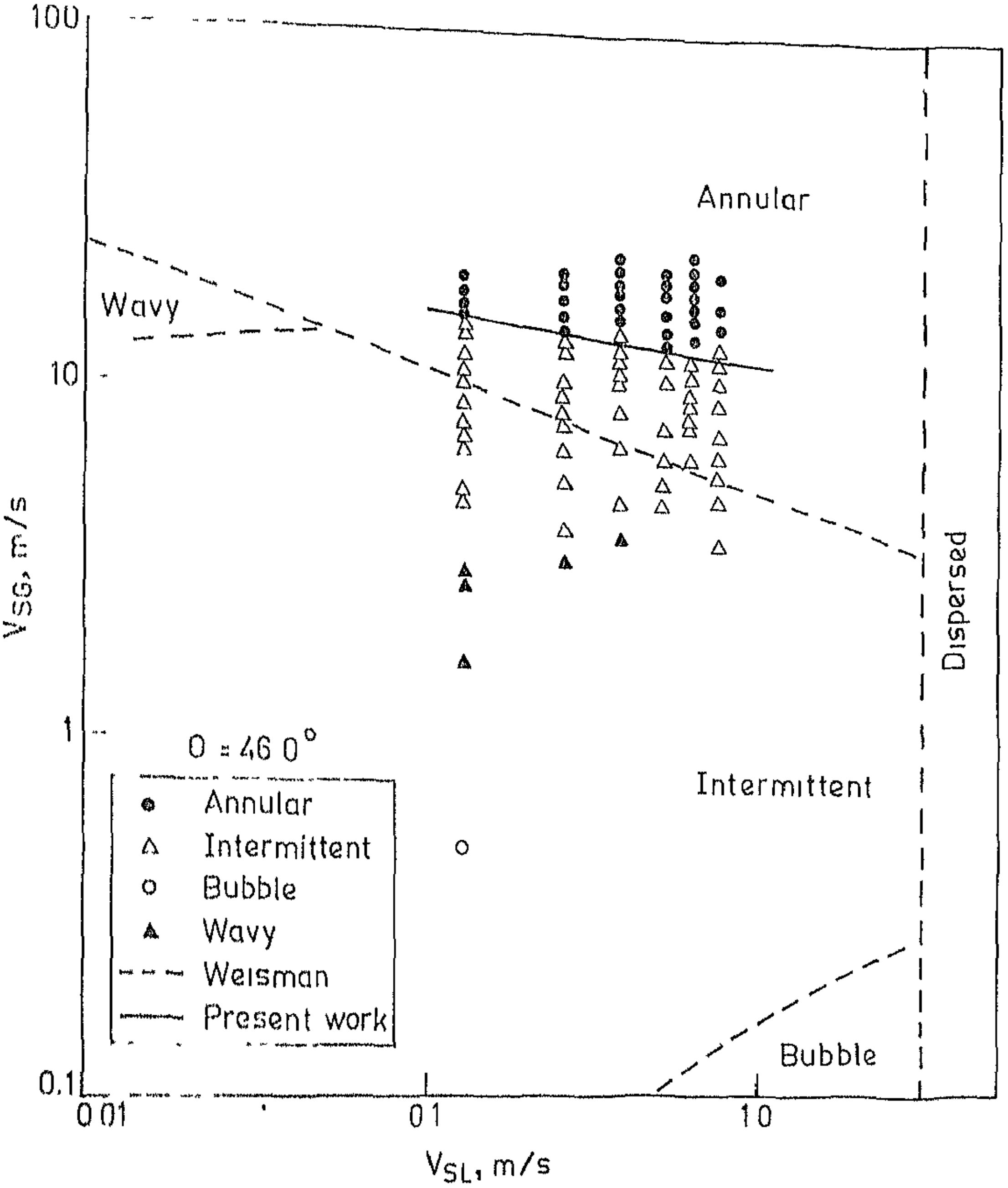


Fig. 4.17C Flow pattern map for θ = 46.0°

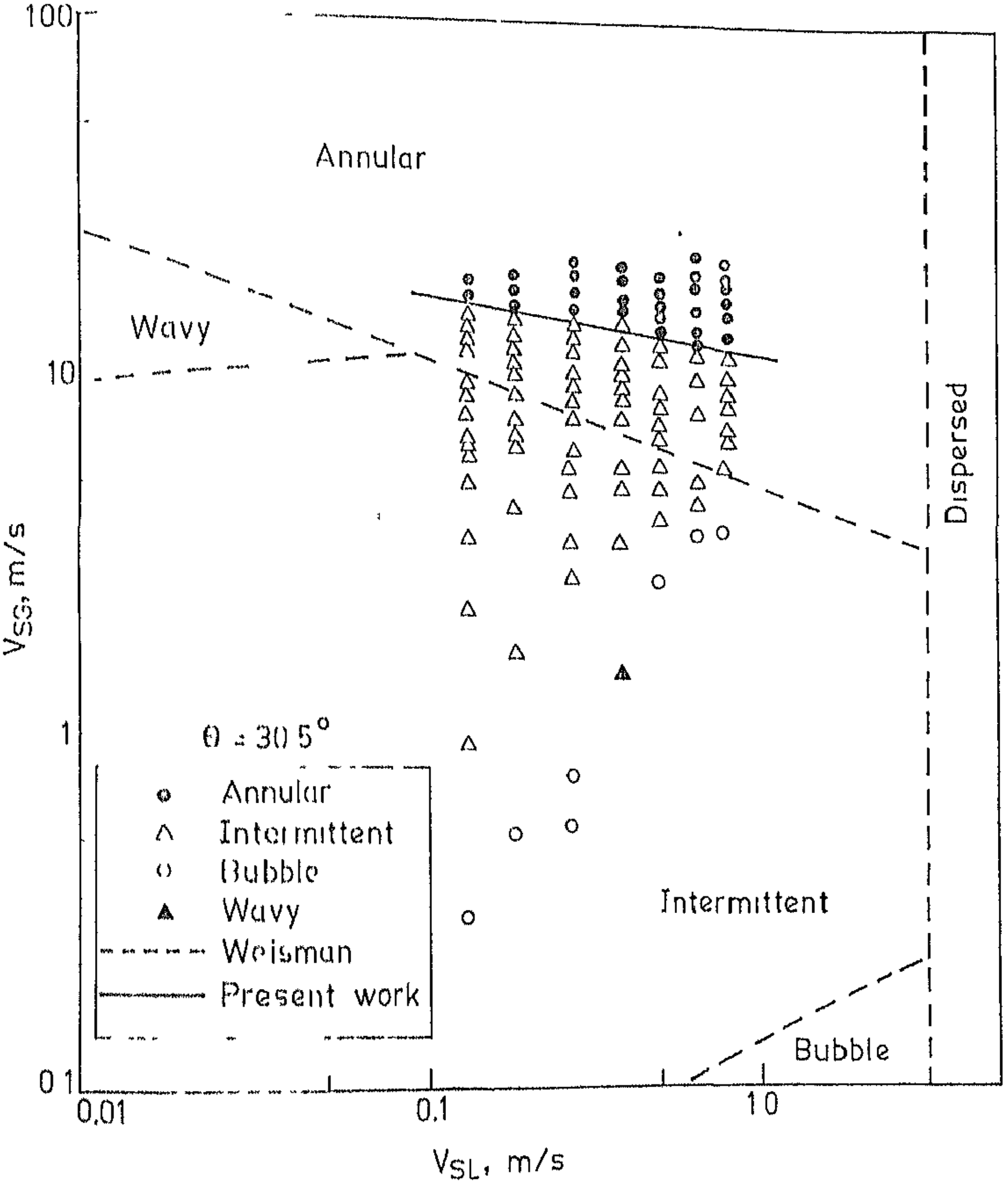


Fig 4 17D Flow pattern map for θ = 30 5°

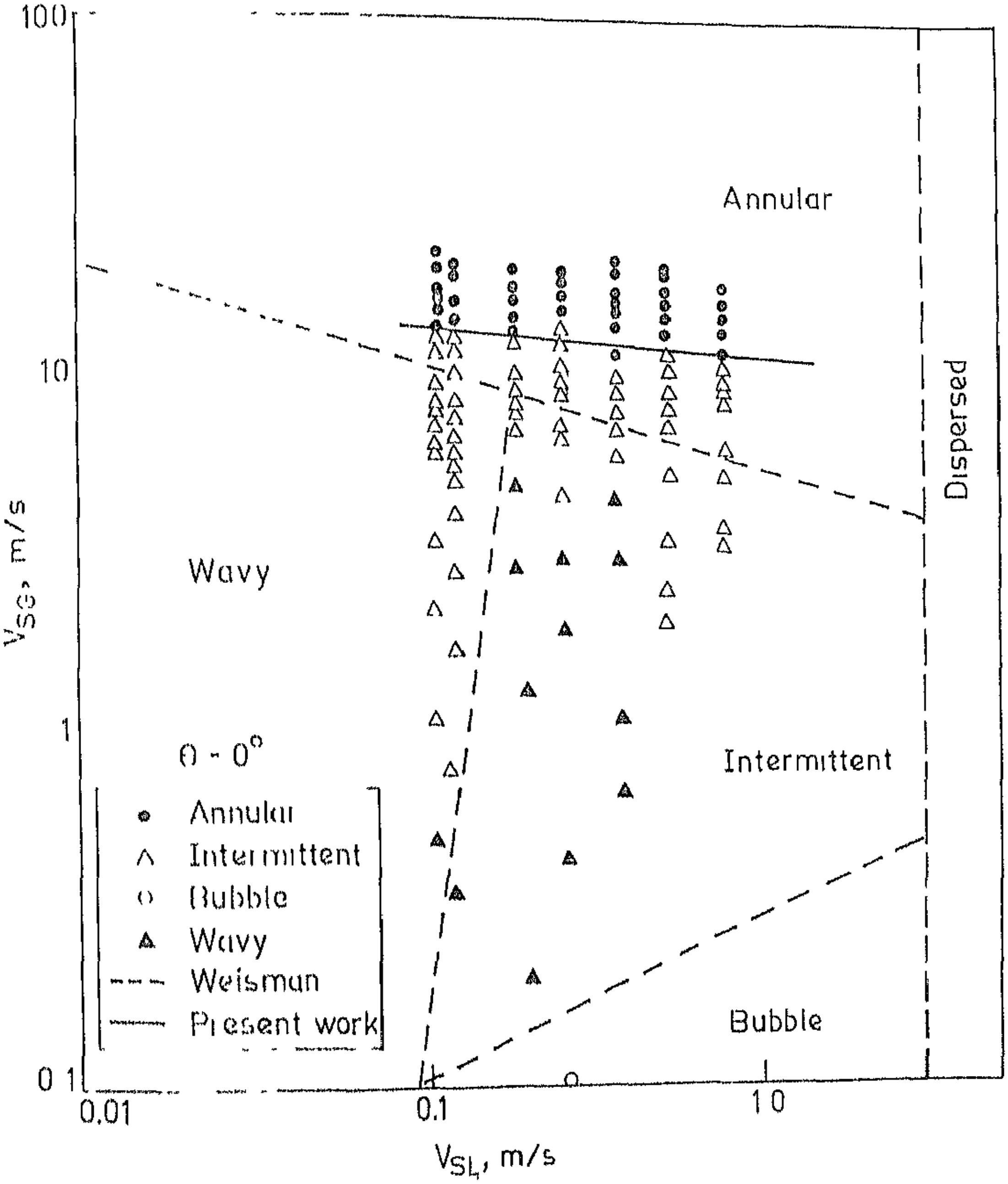


Fig. 4.17E Flow pattern map for θ = 0°

separated wavy and bubbly flow. The dispersed flow was not observed in this study.

The transition from intermittent to annular appears to take place above the line given by Weisman and coworkers (1979, 1981). On the other hand, the line drawn based on the model proposed by Taitel et al. (1980) for vertical case is close to the transition observed in the present work. This is true for all other inclinations as well. The data indicate that the transition from intermittent to annular is relatively unaffected by angle of inclination which is in agreement with the observation of Weisman and coworkers (1979, 1981). For the inclinations 0°, 30° and 45° the wavy flow was observed and the data points fell in the intermittent region indicated by Weisman and Kang.

The bubbly flow was observed only in few runs and the corresponding points on the flow map were observed to be in the lower part of intermittent region of Weisman and coworkers (1979, 1981). In this region any small change in quality resulted in a large upward shift of points on the plot. Small errors in quality could have resulted in the shift above the transition line. Since two-phase mixture is entering the glass-section from boiling zone the bubbles detached at the wall were carried along the liquid which otherwise would have formed slugs after stabilization.

Finally, it may be said that the annular to intermittent transition is not significantly affected by the angle of inclination as observed by Weisman and coworkers (1979, 1981). The separated wavy flow appears to persist from 0° to 45° inclination. The 'anomalous' behaviour of flow patterns in half inch line reported by Weisman and coworkers was not observed in flow boiling.

CHAPTER 5

CONCLUSIONS

Two-phase pressure drop and flow boiling heat transfer were studied in a tube inclined at 0°, 30.5°, 46°, 67.5° and 90° with respect to horizontal using water as the fluid at atmospheric pressure in the range of liquid flow rate qualities and heat fluxes encountered in solar systems.

The boiling heat transfer data indicate that both nucleate and convective heat transfer are significant in the quality range covered in the present study. When the flow patterns were bubbly or intermittent, heat transfer coefficient varied with the angle of inclination and passed through a minimum value at about 50°. This kind of behaviour can be attributed to the variation of void distribution with inclination; which in turn resulted in circumferential variation of contributions due to nucleate boiling and two-phase convective transfer. In annular flow, the variation of heat transfer coefficient with the angle of inclination was found to be not very significant.

It was found that the Chen correlation (1966) represented the heat transfer data in vertical flow boiling better than the Dengler-Addoms (1956) and Bjorge et al. (unpublished) correlations. The Chen correlation was extended for inclined and horizontal cases considering that both the S and F functions depend on the angle of inclination . The average and mean deviations between the experimental and the estimated using the extended Chen correlation were 9.2 % and 0.84 %, respectively.

As there are no reliable void fraction correlations for inclined flow boiling for computing the frictional pressure drop from the total pressure drop, an indirect method was employed for its evaluation. Of the frictional pressure drops computed using the several void fraction correlations for the vertical case, the pressure drop computed using the Dengler-Addoms (1956) correlation gave close agreement with the well known Baroczy (1965) correlation. Hence, this correlation was modified for inclined flow by applying the correction factors proposed by Beggs and Brill (1973) and was employed to compute the frictional pressure drops.

The nature of change of frictional pressure drop with quality was found to depend on the flow pattern. In annular flow, frictional pressure drop with quality was rather less than in intermittent flow. The variation of the frictional pressure drop with the angle of inclination was observed to depend very strongly on mass velocity and quality. Heat flux was found to have no effect on frictional pressure drop in the present range of study.

It is found that the Baroczy correlation could fit most of the frictional pressure drop data within the error bounds of ± 50 % for all inclinations. The Lockhart-Martinelli method of correlation was also attempted. The Lockhart-Martinelli frictional multipliers were correlated with mass velocity, two-phase parameter and the angle of inclination using the exponent multiple regression analysis. The data could be correlated with average and mean deviations of 26.8 % and -8 %, respectively.

The flow pattern observed during heat transfer runs were presented and compared with the transition lines suggested by Weisman and coworkers (1979, 1981). Most of the data fell in the annular and intermittent zone. It was observed that the annular to intermittent transition is not significantly affected by the angle of inclination.

The void fraction, pressure drop and heat transfer correlations proposed in this work would be useful in the design of solar systems involving flow boiling in inclined tubes.

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APPENDIX A

ALGORITHM FOR EVALUATION
OF FUNCTIONS F AND S

APPENDIX A

Chen gave the following iterative method for the evaluation of functions F and S. The initial estimate of F was obtained by plotting (h_{TP}/h_f) versus $(1/X_{tt})$ and drawing a best fit curve. Using this estimate of F, h_N was computed from Equation 2.1 and S versus $(Re.F^{1.25})$ was plotted and the best curve was drawn. Using the first estimate of S, F was computed and replotted to get the second estimate of F. This procedure is repeated until F and S values remained fairly constant.

The above procedure has been adapted for computer calculation. The following algorithm was used to compute C_1, C_2, C_3 and C_4 for each of the inclinations.

(i) Compute $F_i = (h_{TP}/h_f)_i$ for i=1,N. N is the number of points for an inclination, if it is the first iteration; otherwise

$$F_i \left[\frac{h_{TP} - \left\{ C_3 + C_4 \log \left[Re\ 10^{1.25(C_1 + C_2 \log 1/X_{tt})} \right] \right\} h_N}{h_f} \right]_i$$

for i = 1,N

(ii) From the above set of F_i, compute the constants C_1 and C_2 of Equation 4.6A using the method of least-squares with appropriate weightages (the criteria used for giving weightages is given at the end) given to each point and excluding the points for which $F > 1$.

(iii) Compute S_i from the equation,

$$S_i \quad \left[\frac{h_{TP} - h_f\, 10^{(C_1 + C_2 \log 1/X_{tt})}}{h_N}\right]_i \qquad \text{for } i = 1, N$$

(iv) From the above set of S_i, obtain C_3 and C_4 of Equation 4.6B by the method of least squares with weightage given to each point and excluding the points for which $S < 0$ or $S > 1$.

Steps(i) to (iv) are repeated until the average deviation remained more or less constant from iteration to iteration.

Using the F and S curves obtained from the above algorithm as reference curves, the constants C_1, C_2, C_3 and C_4 were refined incorporating a rejection criteria in the steps(ii) and (iv) of the algorithm. According to this rejection criteria, the F_i's and S_i's deviating by more than ± 60 % from the reference curves were rejected in evaluating the constants. This method of refinement gave the lowest least-square error.

Weightage:

The range between the minimum and maximum values of X_{tt} was divided into 20 equal intervals. For each point (F_i or S_i) in an interval a weightage W_i was assigned; where $W_i = 1/N$ and N is the number of points in the interval. This was done as the points are unevenly distributed over the range of X_{tt}.

APPENDIX B

HEAT TRANSFER DATA

G mass velocity, kg/m^{2}s

x = mass vapor quality at the axial location of thermocouples of the test-section, T2

X_{tt} – Lockhart-Martinelli parameter

q/A - heat flux, kW/m^2

T_{Wav} - average of inner surface temperatures, °C

T_b = liquid temperature obtained by linear interpolation of the inlet and outlet liquid temperatures of the test-section, °C

h_{TP} - two-phase heat transfer coefficient, W/m^2 °C

HEAT TRANSFER DATA   ANGLE OF INCLINATION = 90.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
1	750.8	0.014	0.585	229.8	115.46	104.76	21501
2	744.0	0.015	0.643	123.6	110.57	104.47	20265
3	753.9	0.015	0.630	51.4	107.20	104.15	16908
4	750.1	0.010	0.427	226.4	115.39	103.83	19583
5	760.0	0.011	0.486	123.3	111.49	104.24	16990
6	761.5	0.011	0.475	51.9	107.42	103.79	14340
7	749.3	0.006	0.294	226.2	115.37	102.73	17923
8	761.5	0.007	0.323	125.1	112.30	103.27	13846
9	753.9	0.007	0.320	53.0	107.48	103.13	12194
10	749.3	0.003	0.159	222.9	116.19	101.69	15380
11	756.9	0.004	0.178	128.2	112.68	102.07	12081
12	756.9	0.003	0.176	51.5	106.80	101.93	10579
13	743.2	0.014	0.596	225.5	115.74	104.84	20693
14	749.3	0.013	0.539	221.7	115.80	104.59	19780
15	749.3	0.011	0.489	227.0	115.68	104.08	19580
16	749.3	0.012	0.517	225.4	115.65	104.56	20330
17	749.3	0.010	0.433	225.5	116.20	104.08	18646
18	746.3	0.008	0.375	227.4	116.20	103.76	18280
19	747.8	0.009	0.407	231.2	115.92	103.70	18923
20	748.6	0.009	0.395	233.7	116.81	103.74	17871
21	758.4	0.005	0.243	231.7	116.38	102.59	16826
22	749.3	0.007	0.325	227.3	115.25	102.79	18244
23	755.4	0.007	0.304	227.6	116.47	102.94	16827
24	756.9	0.005	0.250	226.2	116.85	102.63	15928
25	511.2	0.027	1.104	224.5	113.67	103.41	21903
26	507.4	0.028	1.130	128.5	109.04	103.11	21662
27	511.9	0.027	1.110	52.2	105.70	102.83	18207
28	509.7	0.022	0.903	225.1	113.95	102.82	20234
29	511.9	0.021	0.905	127.1	109.07	102.37	18967
30	514.9	0.014	0.607	225.5	114.72	102.27	18117
31	511.9	0.014	0.616	132.2	109.71	101.83	16792
32	513.4	0.012	0.536	51.2	105.02	101.31	13832
33	508.9	0.007	0.309	226.4	116.70	102.21	15630
34	505.9	0.006	0.292	128.6	111.94	102.12	13102
35	508.2	0.006	0.277	50.8	106.28	101.59	10835
36	507.4	0.027	1.117	231.2	113.80	103.32	22088
37	510.4	0.025	1.030	225.4	113.77	103.28	21486
38	512.7	0.023	0.960	223.9	113.32	103.00	21711
39	511.9	0.024	1.009	226.3	113.67	103.11	21458
40	510.4	0.020	0.855	226.1	113.97	102.76	20172
41	510.4	0.018	0.766	226.8	113.88	102.32	19989
42	511.9	0.020	0.826	223.2	114.00	102.72	19797
43	510.5	0.018	0.763	223.3	114.03	102.55	19462
44	510.4	0.013	0.562	222.4	114.34	102.23	18370
45	507.4	0.012	0.553	224.8	114.58	102.19	18148
46	510.4	0.014	0.617	228.8	115.08	102.46	18128
47	510.4	0.011	0.490	224.8	115.48	102.49	17298
48	409.4	0.022	0.915	53.7	105.27	102.00	16441
49	380.0	0.040	1.614	229.5	113.14	102.87	22357
50	379.1	0.038	1.525	126.6	108.58	102.19	19824

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 90.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
51	379.1	0.037	1.507	51.5	105.05	102.12	17632
52	378.3	0.032	1.294	227.4	113.69	102.40	20153
53	378.3	0.030	1.235	126.8	108.76	101.88	18434
54	378.3	0.029	1.211	51.5	104.77	101.56	16071
55	381.6	0.021	0.890	227.1	114.38	101.80	18055
56	366.8	0.019	0.840	129.3	110.02	101.43	15040
57	381.6	0.017	0.748	51.3	105.11	101.15	12964
58	378.3	0.010	0.465	224.8	114.95	101.53	16756
59	380.0	0.006	0.279	130.3	112.56	101.83	12152
60	380.0	0.004	0.220	50.9	107.65	101.83	8767
61	380.0	0.039	1.554	230.8	113.24	102.79	22096
62	378.3	0.035	1.420	230.0	113.35	102.46	21122
63	378.3	0.031	1.259	229.7	113.50	102.16	20281
64	379.8	0.034	1.377	229.0	113.38	102.40	20879
65	378.3	0.027	1.136	229.5	113.97	102.07	19298
66	379.1	0.023	0.995	231.1	113.89	101.67	18928
67	394.8	0.025	1.037	235.8	114.42	101.84	18748
68	379.1	0.023	0.987	227.9	114.36	101.86	18238
69	378.3	0.016	0.700	229.0	114.90	101.53	17132
70	370.1	0.020	0.866	218.4	113.81	101.75	18123
71	378.3	0.016	0.691	228.2	115.01	101.73	17198
72	378.3	0.012	0.545	229.1	115.30	101.72	16884
73	244.2	0.058	2.340	226.6	113.88	100.66	17154
74	254.4	0.056	2.285	126.7	109.15	101.00	15548
75	254.4	0.054	2.204	53.2	104.44	100.78	14529
76	253.8	0.041	1.695	227.4	114.85	100.53	15880
77	254.9	0.042	1.716	128.7	110.60	100.84	13180
78	255.5	0.040	1.643	51.8	104.81	100.52	12106
79	253.8	0.024	1.047	227.0	114.49	100.34	16051
80	257.3	0.023	0.981	131.5	110.53	100.60	13258
81	256.7	0.021	0.908	53.6	105.75	100.48	10172
82	253.8	0.009	0.428	226.5	113.36	100.36	17428
83	257.3	0.004	0.196	130.9	111.71	100.56	11752
84	257.3	0.003	0.151	51.3	108.68	100.70	6426
85	251.4	0.055	2.227	231.4	115.05	101.15	16657
86	254.9	0.047	1.911	230.6	115.60	100.83	15619
87	254.9	0.041	1.705	232.4	115.96	100.88	15416
88	257.3	0.045	1.843	233.7	115.78	101.02	15838
89	253.8	0.036	1.487	230.5	116.10	100.94	15211
90	254.4	0.030	1.262	231.9	115.25	100.59	15834
91	254.9	0.034	1.421	232.1	115.61	100.90	15786
92	254.9	0.030	1.267	232.4	115.40	100.82	15939
93	257.9	0.022	0.944	228.9	115.10	101.00	16249
94	253.8	0.025	1.062	226.5	114.12	100.35	16458
95	256.7	0.018	0.795	237.5	115.95	100.91	15800
96	257.9	0.013	0.694	230.3	115.58	100.91	15708
97	189.9	0.070	2.834	230.4	115.76	100.63	15223
98	188.1	0.070	2.832	126.0	109.99	100.65	13485
99	188.1	0.069	2.784	50.8	104.54	100.51	12616
100	190.5	0.053	2.149	230.0	116.05	100.77	15067

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 90.0°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
101	194.1	0.045	1.868	129.7	111.82	100.47	11428
102	193.9	0.043	1.796	51.5	105.26	100.26	10316
103	189.0	0.038	1.570	225.8	115.56	100.60	15104
104	189.3	0.024	1.021	128.5	111.86	100.42	11237
105	189.3	0.023	0.981	51.7	106.18	100.21	8667
106	188.7	0.012	0.534	225.9	114.02	100.28	16449
107	190.5	0.005	0.245	130.5	111.52	100.52	11867
108	190.5	0.003	0.174	51.1	106.46	100.64	8780
109	183.4	0.069	2.775	225.6	116.37	101.06	14734
110	189.3	0.059	2.362	226.0	116.37	101.03	14741
111	189.3	0.051	2.056	224.7	115.66	100.99	15328
112	190.5	0.060	2.438	228.2	115.51	100.62	15327
113	186.9	0.044	1.824	228.9	114.98	100.79	16140
114	186.9	0.038	1.586	231.2	113.89	100.57	17366
115	188.1	0.046	1.897	231.5	114.59	100.86	16883
116	189.1	0.039	1.600	231.0	114.16	100.68	17146
117	188.1	0.023	1.008	230.5	113.26	100.69	18338
118	181.1	0.023	1.000	231.9	114.79	100.85	16641
119	188.1	0.022	0.955	231.0	114.73	100.87	16690
120	186.5	0.014	0.627	231.3	114.48	100.76	16873
121	125.5	0.108	4.327	222.8	116.63	100.74	14026
122	125.9	0.104	4.194	126.6	110.80	100.46	12240
123	125.9	0.101	4.064	51.0	104.88	100.26	11051
124	124.8	0.079	3.170	225.2	117.12	100.70	13715
125	124.8	0.078	3.136	125.6	111.89	100.40	10933
126	125.9	0.074	2.994	51.7	105.50	100.23	9797
127	122.4	0.043	1.752	224.8	116.76	100.88	14155
128	126.5	0.044	1.767	122.7	114.18	102.22	10256
129	125.9	0.042	1.670	50.7	108.43	102.43	8454
130	125.5	0.017	0.736	223.4	115.60	100.72	15034
131	128.0	0.009	0.414	124.5	113.71	102.41	11017
132	128.2	0.005	0.229	52.2	110.74	102.42	6274
133	127.3	0.100	4.029	227.4	116.73	100.58	14081
134	128.9	0.086	3.449	226.2	116.81	100.58	13937
135	130.0	0.074	2.994	226.5	116.01	100.54	14645
136	126.9	0.087	3.484	222.2	116.66	100.75	13973
137	126.5	0.067	2.724	224.8	115.69	100.50	14802
138	125.7	0.054	2.206	224.5	115.18	100.73	15553
139	123.3	0.065	2.625	222.0	115.69	100.68	14788
140	122.7	0.056	2.278	221.7	115.59	100.69	14883
141	126.4	0.034	1.415	227.6	114.51	100.28	16011
142	124.2	0.042	1.745	227.2	114.81	100.59	15979
143	125.3	0.036	1.482	230.6	114.48	100.71	16748
144	123.3	0.023	0.999	224.5	114.16	100.74	16751

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 67.5°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
1	760.5	0.017	0.688	225.2	117.30	105.86	19694
2	756.9	0.017	0.697	125.3	111.88	104.99	18229
3	750.8	0.017	0.712	49.7	107.91	104.52	14886
4	760.0	0.012	0.519	224.6	113.89	104.42	23782
5	758.4	0.012	0.531	127.8	112.17	104.60	16928
6	753.9	0.012	0.518	50.6	107.87	104.13	13626
7	756.2	0.008	0.360	223.6	117.58	103.93	16381
8	760.0	0.008	0.354	128.1	112.57	103.90	14788
9	763.0	0.007	0.332	50.3	108.40	103.82	11049
10	764.5	0.004	0.206	224.6	117.97	102.71	14713
11	759.2	0.004	0.181	128.3	113.74	102.66	11589
12	764.5	0.003	0.148	49.9	107.37	102.36	9991
13	755.4	0.017	0.716	224.8	115.42	105.01	21607
14	755.4	0.015	0.638	224.9	115.18	104.41	20897
15	756.2	0.014	0.582	225.2	115.22	104.40	20816
16	750.8	0.014	0.578	224.3	117.38	104.91	17989
17	760.0	0.011	0.478	223.6	117.71	104.64	17109
18	756.9	0.009	0.406	223.5	117.77	104.41	16735
19	760.0	0.010	0.455	223.9	117.22	104.43	17510
20	772.1	0.010	0.419	223.2	117.16	104.28	17329
21	749.3	0.007	0.319	223.2	118.18	103.56	15271
22	746.3	0.010	0.420	224.6	117.31	104.14	17050
23	744.8	0.008	0.369	225.3	117.40	103.88	16659
24	747.8	0.007	0.326	225.3	117.89	103.37	15526
25	502.9	0.028	1.110	226.3	114.82	104.61	22165
26	495.4	0.027	1.077	124.7	109.93	103.84	20467
27	495.4	0.026	1.052	49.7	106.32	103.46	17441
28	499.9	0.022	0.897	226.1	114.97	103.87	20376
29	511.9	0.020	0.828	126.9	109.97	103.21	18762
30	507.4	0.020	0.828	50.5	106.21	103.07	16096
31	499.9	0.014	0.614	224.8	115.88	103.39	17997
32	504.4	0.013	0.562	123.7	110.57	102.87	16061
33	502.9	0.011	0.501	51.8	106.09	102.17	13219
34	499.9	0.007	0.301	225.0	117.82	103.24	15439
35	499.9	0.005	0.225	127.9	112.24	102.63	13304
36	499.9	0.004	0.176	50.6	107.99	102.38	9028
37	499.9	0.027	1.069	226.7	114.55	104.29	22097
38	499.9	0.024	0.962	226.1	114.54	103.98	21424
39	502.9	0.021	0.867	225.0	114.36	103.79	21262
40	510.4	0.023	0.943	224.6	114.46	104.15	21776
41	511.9	0.018	0.769	222.4	114.26	103.31	20332
42	513.4	0.016	0.676	221.1	114.40	103.35	20020
43	493.9	0.019	0.791	226.4	115.96	104.05	19029
44	499.9	0.016	0.663	226.9	115.93	103.41	18128
45	499.9	0.011	0.489	228.6	117.02	103.20	16542
46	502.9	0.013	0.562	226.5	116.02	103.34	17867
47	502.9	0.011	0.487	223.1	116.42	103.25	16955
48	500.7	0.009	0.384	224.0	117.30	103.33	16032
49	380.0	0.037	1.460	226.5	114.06	103.39	21238
50	388.2	0.036	1.437	127.2	109.99	103.55	19727

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 67.5°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
51	388.2	0.035	1.399	52.2	106.21	103.26	17655
52	378.3	0.028	1.159	225.6	114.57	102.89	19319
53	384.9	0.027	1.130	123.5	109.80	102.69	17376
54	384.9	0.028	1.141	51.2	105.99	102.75	15837
55	378.3	0.018	0.754	224.4	116.08	102.86	16966
56	386.5	0.019	0.799	126.4	110.44	102.44	15811
57	386.5	0.017	0.750	50.0	105.89	102.31	13964
58	383.2	0.008	0.368	224.5	118.18	102.82	14618
59	378.3	0.007	0.329	126.9	111.98	102.68	13674
60	380.0	0.007	0.314	51.0	107.89	102.69	9806
61	383.2	0.034	1.370	232.5	114.98	103.58	20389
62	380.0	0.030	1.221	222.4	114.79	103.51	19721
63	375.0	0.027	1.099	226.9	115.12	103.24	19100
64	370.1	0.030	1.229	231.0	115.28	103.49	19593
65	375.0	0.030	1.197	229.9	115.26	103.39	19384
66	378.3	0.022	0.935	230.1	115.61	103.08	18373
67	378.3	0.025	1.030	225.0	115.15	103.19	18827
68	380.0	0.023	0.943	223.7	115.44	103.19	18270
69	383.2	0.014	0.625	222.1	116.23	102.89	16659
70	380.0	0.020	0.844	225.8	115.60	103.11	18075
71	379.9	0.018	0.745	231.7	115.82	102.91	17954
72	378.3	0.014	0.599	231.2	116.85	103.21	16956
73	251.4	0.057	2.236	221.9	114.92	102.85	18401
74	249.0	0.055	2.165	124.3	110.36	102.49	15789
75	254.9	0.051	2.040	50.1	105.84	102.13	13539
76	257.3	0.040	1.632	227.4	115.68	102.30	17000
77	256.7	0.041	1.654	124.5	110.68	102.34	14927
78	253.1	0.040	1.611	49.8	106.55	102.40	11988
79	258.5	0.027	1.123	221.0	116.84	102.46	15390
80	250.2	0.026	1.084	124.6	112.61	102.29	12077
81	249.0	0.025	1.034	50.6	107.11	102.31	10562
82	249.0	0.007	0.328	222.8	116.30	102.37	16000
83	250.2	0.005	0.232	127.0	114.14	102.36	10792
84	251.4	0.003	0.173	51.3	108.62	102.29	8102
85	251.4	0.053	2.114	223.7	115.60	102.41	16973
86	254.4	0.046	1.852	225.2	115.90	102.37	16658
87	253.5	0.039	1.600	222.6	115.86	101.95	16026
88	253.8	0.047	1.864	226.1	115.97	102.37	16633
89	253.8	0.037	1.487	226.5	116.47	102.27	15964
90	253.8	0.031	1.270	226.8	116.59	102.23	15809
91	245.8	0.039	1.556	224.6	116.76	102.80	16093
92	253.1	0.033	1.354	225.5	116.91	102.69	15871
93	252.6	0.021	0.883	224.9	116.67	102.51	15905
94	253.1	0.025	1.019	223.9	116.72	102.69	15969
95	253.1	0.021	0.877	223.9	116.70	102.69	15979
96	252.0	0.014	0.602	219.5	116.42	102.60	15886
97	189.3	0.080	3.109	225.2	115.85	102.58	16978
98	186.9	0.074	2.894	122.6	110.84	102.27	14005
99	186.9	0.070	2.768	51.2	106.14	102.10	12658
100	188.7	0.059	2.326	224.9	116.64	102.25	15640

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 67.5°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
101	189.3	0.057	2.263	127.2	111.80	102.07	13078
102	190.5	0.053	2.136	50.3	106.49	102.00	11356
103	189.3	0.035	1.436	226.0	116.68	102.10	15505
104	189.3	0.032	1.312	126.3	112.60	101.97	11892
105	189.3	0.029	1.211	51.1	106.93	101.79	9949
106	187.5	0.009	0.428	224.3	116.38	102.06	15675
107	186.3	0.006	0.303	126.3	114.31	102.25	10472
108	186.3	0.004	0.188	50.4	108.04	102.00	8349
109	189.3	0.070	2.770	230.0	115.87	101.96	16543
110	182.8	0.064	2.546	226.8	116.21	101.76	15702
111	189.3	0.055	2.195	230.1	116.37	101.73	15723
112	188.1	0.063	2.500	226.1	115.83	101.64	15933
113	189.9	0.049	1.985	227.0	116.46	101.72	15417
114	189.3	0.041	1.684	225.7	116.47	101.71	15300
115	192.3	0.048	1.904	224.9	117.75	102.16	14433
116	193.5	0.042	1.696	225.5	117.66	102.00	14409
117	193.9	0.026	1.099	222.6	117.59	102.10	14387
118	187.9	0.034	1.374	225.2	117.71	102.16	14489
119	189.1	0.028	1.162	221.8	117.61	102.17	14374
120	190.5	0.019	0.799	222.4	117.19	101.94	14592
121	127.8	0.110	4.302	225.6	117.58	102.05	14528
122	126.9	0.105	4.122	125.8	112.33	101.90	12069
123	127.1	0.101	3.980	50.9	106.58	101.68	10391
124	127.1	0.079	3.101	225.0	117.81	101.89	14144
125	127.1	0.073	2.904	124.3	113.26	101.67	10727
126	125.9	0.071	2.807	51.6	107.16	101.64	9365
127	125.9	0.042	1.677	225.1	117.70	102.17	14505
128	125.7	0.039	1.582	126.3	114.78	102.03	9909
129	125.9	0.038	1.536	51.0	107.71	101.87	8736
130	124.2	0.012	0.554	224.3	116.97	102.07	15053
131	124.2	0.008	0.351	126.7	114.58	101.96	10052
132	124.2	0.003	0.166	51.0	110.48	101.77	5880
133	124.2	0.099	3.897	224.4	117.95	102.01	14090
134	120.9	0.087	3.423	224.5	117.73	101.89	14188
135	126.5	0.075	2.950	224.4	117.33	101.98	14631
136	128.2	0.083	3.283	231.1	117.65	101.90	14682
137	125.3	0.063	2.519	223.1	117.24	101.62	14288
138	125.9	0.053	2.141	226.8	116.87	101.84	15099
139	125.9	0.064	2.536	226.5	117.28	101.68	14529
140	127.1	0.054	2.168	226.7	117.24	101.78	14670
141	127.1	0.032	1.319	226.7	115.81	101.73	16114
142	126.5	0.037	1.528	225.4	116.03	101.79	15835
143	125.7	0.025	1.071	222.3	115.54	101.79	16178
144	129.9	0.013	0.574	226.2	114.81	101.93	17579

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 46.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
1	761.7	0.004	0.198	227.7	120.61	103.32	14066
2	756.9	0.003	0.163	133.2	114.73	103.03	11390
3	753.9	0.011	0.467	227.7	118.71	106.14	18150
4	738.7	0.011	0.457	133.7	114.38	105.90	15781
5	743.2	0.010	0.428	49.5	109.60	105.67	12600
6	761.5	0.014	0.571	227.5	118.19	106.82	20049
7	743.2	0.014	0.578	133.8	113.13	106.03	18858
8	743.2	0.014	0.581	50.8	108.97	105.79	15994
9	753.9	0.010	0.426	227.1	116.77	107.21	23800
10	746.3	0.019	0.759	132.3	112.64	106.87	22964
11	746.3	0.019	0.744	50.6	108.86	106.27	19619
12	769.1	0.009	0.376	229.5	122.18	106.62	14757
13	769.1	0.008	0.347	133.9	117.35	106.09	11890
14	766.0	0.008	0.336	51.1	110.70	106.00	10864
15	517.9	0.009	0.397	232.2	120.50	105.01	15004
16	508.9	0.008	0.354	132.7	115.99	104.92	11995
17	522.4	0.007	0.305	51.6	111.02	104.90	8425
18	514.9	0.017	0.711	230.7	118.30	105.18	17593
19	514.9	0.016	0.678	133.9	113.22	104.72	15765
20	523.9	0.015	0.629	51.4	108.21	104.65	14411
21	499.9	0.023	0.932	234.7	117.36	105.87	20440
22	514.9	0.022	0.870	133.5	112.42	105.31	18820
23	529.9	0.021	0.831	51.2	108.26	105.20	16737
24	499.9	0.028	1.097	227.0	115.81	105.60	22246
25	520.9	0.026	1.034	134.3	111.84	105.46	21085
26	508.9	0.026	1.051	51.2	107.97	105.27	18964
27	514.9	0.026	1.012	230.7	115.84	105.69	22741
28	533.7	0.023	0.908	229.1	115.82	105.28	21761
29	525.4	0.020	0.818	228.9	115.79	105.07	21373
30	516.4	0.024	0.969	231.7	115.62	105.40	22680
31	513.4	0.020	0.828	230.7	115.91	104.85	20872
32	522.4	0.017	0.719	232.2	116.11	104.50	20012
33	508.9	0.021	0.849	230.9	117.64	105.77	19466
34	507.4	0.019	0.776	230.0	117.98	105.72	18762
35	507.4	0.014	0.597	225.2	118.55	105.26	16947
36	510.4	0.016	0.667	226.2	118.04	105.40	17900
37	522.4	0.014	0.582	232.6	119.09	105.59	17250
38	522.4	0.012	0.487	232.9	119.06	105.52	17212
39	370.9	0.010	0.447	232.6	118.86	104.60	16336
40	370.9	0.008	0.357	136.0	114.77	104.33	13089
41	384.9	0.006	0.292	53.7	110.12	104.21	9087
42	375.0	0.021	0.871	234.5	117.90	104.41	17393
43	379.1	0.019	0.797	136.6	113.11	104.31	15500
44	387.4	0.018	0.750	52.8	108.00	104.12	13600
45	383.2	0.030	1.187	234.1	117.96	105.04	18129
46	380.0	0.029	1.152	136.9	112.86	104.76	16918
47	380.0	0.029	1.138	55.5	108.03	104.53	15573
48	370.1	0.040	1.553	232.8	117.30	105.42	19390
49	381.6	0.038	1.473	137.9	112.15	104.97	19240
50	383.2	0.035	1.395	53.0	107.11	104.20	18214

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 46.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
51	372.6	0.035	1.376	234.1	115.38	104.39	21325
52	401.4	0.029	1.173	235.5	115.60	104.42	21078
53	391.5	0.027	1.076	234.6	115.60	103.99	20229
54	354.6	0.037	1.451	227.5	117.21	105.13	18851
55	363.5	0.028	1.109	231.2	117.96	104.92	17744
56	375.0	0.023	0.944	239.4	118.45	104.81	17564
57	383.2	0.026	1.032	230.2	117.40	104.67	18102
58	363.5	0.024	0.966	235.1	117.17	104.10	17990
59	395.6	0.019	0.782	241.0	117.44	104.01	17967
60	371.7	0.018	0.743	234.1	117.75	104.05	17148
61	371.7	0.020	0.830	234.4	117.11	104.07	17992
62	380.0	0.017	0.696	232.7	117.10	104.12	17949
63	371.7	0.014	0.574	233.0	115.54	104.35	20820
64	248.4	0.012	0.499	231.4	117.76	103.96	16833
65	229.9	0.010	0.449	138.0	113.08	103.76	14828
66	254.9	0.007	0.320	52.4	109.84	103.66	8472
67	237.0	0.031	1.240	237.9	117.87	103.80	16914
68	243.0	0.027	1.108	136.4	114.74	103.69	12346
69	258.5	0.024	0.992	51.7	108.38	103.36	10295
70	225.1	0.058	2.107	237.5	121.75	107.38	16524
71	260.9	0.039	1.551	128.7	112.81	103.25	13469
72	243.0	0.031	1.243	51.2	108.44	103.50	10479
73	243.0	0.051	1.988	228.4	118.27	103.67	15652
74	257.3	0.047	1.858	137.7	113.51	103.56	13840
75	249.0	0.046	1.823	52.1	107.67	103.25	11792
76	260.9	0.049	1.900	230.1	118.53	103.77	15592
77	251.4	0.045	1.771	230.5	118.64	103.64	15370
78	249.0	0.039	1.562	227.8	118.25	103.56	15513
79	263.3	0.045	1.760	232.6	117.83	103.52	16268
80	258.5	0.035	1.416	235.7	117.86	103.41	16280
81	258.5	0.030	1.223	238.4	117.86	103.35	16434
82	258.5	0.035	1.394	239.7	117.78	103.24	16500
83	257.3	0.030	1.207	239.7	117.61	103.20	16643
84	254.9	0.019	0.804	238.2	116.86	103.16	17399
85	250.2	0.021	0.893	239.7	117.23	103.14	17017
86	251.4	0.017	0.723	239.4	116.93	103.13	17339
87	247.8	0.012	0.517	239.0	116.24	103.22	18357
88	125.9	0.098	3.748	223.7	119.48	103.52	14019
89	125.9	0.091	3.505	134.9	115.42	103.29	11127
90	128.2	0.084	3.257	51.3	108.10	102.95	10020
91	116.7	0.074	2.871	222.2	118.41	103.11	14534
92	130.6	0.064	2.483	136.8	115.57	102.95	10841
93	125.9	0.062	2.430	53.2	108.36	102.76	9503
94	124.8	0.047	1.865	238.4	117.85	102.84	15885
95	128.2	0.042	1.691	137.7	115.55	102.90	10892
96	128.2	0.038	1.550	53.7	108.46	102.66	9250
97	124.8	0.012	0.523	232.0	115.54	102.55	17860
98	128.2	0.006	0.292	136.5	112.88	102.40	13059
99	125.9	0.014	0.603	51.6	107.79	102.52	9805
100	120.1	0.091	3.478	232.9	119.27	103.51	14781

Contd....

HEAT TRANSFER DATA ANGLE OF INCLINATION = 46.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
101	124.8	0.077	2.968	229.2	119.10	103.52	14713
102	131.7	0.061	2.367	224.8	118.68	103.45	14800
103	135.2	0.080	3.060	239.5	119.25	103.57	15274
104	130.6	0.063	2.438	240.3	118.86	103.43	15585
105	137.5	0.048	1.889	233.1	118.51	103.42	15457

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 30.5°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
1	776.7	0.005	0.244	234.1	118.68	104.24	16230
2	753.9	0.005	0.237	126.7	113.62	104.02	13201
3	761.5	0.009	0.416	50.8	108.33	103.64	10831
4	761.5	0.009	0.384	225.5	116.99	105.54	19715
5	738.7	0.009	0.386	127.3	112.36	105.24	17889
6	738.7	0.008	0.367	50.2	108.86	105.19	13705
7	738.7	0.014	0.567	225.6	116.06	106.33	23201
8	738.7	0.013	0.533	127.1	111.97	105.87	20850
9	741.7	0.012	0.496	51.1	108.70	105.63	16697
10	746.3	0.018	0.729	224.8	116.86	107.09	23016
11	727.3	0.018	0.738	129.0	112.35	106.33	21075
12	734.9	0.017	0.705	51.0	108.85	105.99	17867
13	712.1	0.018	0.721	222.8	116.30	106.51	22778
14	719.7	0.016	0.650	223.2	116.39	106.19	21894
15	761.0	0.012	0.511	219.1	118.10	106.26	18505
16	749.3	0.013	0.540	219.1	117.21	106.33	20130
17	770.6	0.010	0.445	218.5	117.61	105.86	18606
18	765.3	0.009	0.407	217.5	117.81	105.66	17906
19	756.9	0.009	0.403	218.2	117.43	106.23	19490
20	765.3	0.010	0.322	218.7	135.74	124.15	18883
21	765.3	0.008	0.351	216.9	116.82	105.03	18400
22	776.7	0.007	0.324	213.1	117.46	104.87	16919
23	750.1	0.008	0.363	228.4	117.46	105.09	18460
24	743.2	0.007	0.317	229.3	117.51	104.66	17845
25	752.4	0.006	0.261	229.9	118.00	104.32	16809
26	477.4	0.007	0.311	231.8	119.96	104.17	14685
27	526.9	0.005	0.234	130.6	115.43	103.68	11110
28	529.9	0.004	0.187	51.8	109.50	103.50	8627
29	522.4	0.023	0.914	227.8	116.59	105.26	20122
30	522.4	0.022	0.886	124.5	111.76	104.85	18021
31	522.4	0.021	0.871	51.7	108.02	104.57	14991
32	522.4	0.018	0.749	229.6	116.36	105.04	20295
33	510.4	0.019	0.771	130.8	112.01	104.80	18165
34	522.4	0.018	0.732	51.1	108.06	104.53	14513
35	507.4	0.011	0.458	225.3	118.11	105.00	17161
36	533.7	0.010	0.438	129.2	113.64	105.09	15108
37	514.9	0.010	0.436	50.8	109.97	104.81	11643
38	477.4	0.022	0.901	225.7	117.27	105.36	18978
39	507.4	0.018	0.747	227.9	117.40	105.21	18736
40	507.4	0.016	0.657	223.2	117.37	104.84	17825
41	492.4	0.020	0.809	231.1	117.16	105.00	20700
42	504.4	0.017	0.706	230.6	116.42	104.84	19919
43	526.9	0.013	0.557	224.9	116.85	104.87	18779
44	529.9	0.017	0.700	230.8	115.93	105.04	21209
45	526.2	0.014	0.571	225.9	116.43	104.97	19714
46	525.4	0.010	0.423	226.6	116.11	104.40	19353
47	525.4	0.010	0.428	225.0	117.02	104.34	17751
48	514.9	0.008	0.358	223.6	116.44	103.79	17675
49	518.7	0.005	0.252	223.9	117.64	103.36	15674
50	377.5	0.033	1.310	227.8	117.30	105.04	18602

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 30.5°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
101	197.7	0.008	0.356	229.5	117.12	102.65	15861
102	191.7	0.048	1.861	229.0	118.54	104.05	15812
103	195.3	0.044	1.724	135.4	114.65	103.83	12508
104	184.5	0.044	1.720	52.7	108.60	103.54	10418
105	198.9	0.030	1.212	229.2	117.25	103.63	16829
106	194.1	0.028	1.142	134.1	114.43	103.59	12373
107	203.6	0.024	0.991	52.6	108.06	103.36	11299
108	195.3	0.004	0.208	133.8	115.29	102.41	10408
109	191.7	0.002	0.096	51.9	111.34	100.72	5102
110	191.7	0.057	2.223	229.1	118.00	103.48	15785
111	191.7	0.052	2.031	228.6	117.87	103.44	15854
112	191.7	0.044	1.742	229.2	117.99	103.44	15768
113	195.3	0.055	2.139	228.3	117.64	103.43	16075
114	192.9	0.043	1.690	228.1	117.81	103.42	15862
115	192.9	0.035	1.411	228.0	117.74	103.41	15927
116	191.7	0.043	1.697	228.1	117.37	103.29	16210
117	191.7	0.038	1.519	228.2	117.32	103.25	16224
118	191.7	0.023	0.940	228.0	116.97	103.17	16520
119	189.3	0.033	1.321	227.0	117.61	103.25	15817
120	199.3	0.028	1.134	227.8	117.42	103.19	16016
121	191.7	0.020	0.825	227.5	116.91	103.21	16605
122	134.0	0.086	3.304	229.2	118.14	103.18	15332
123	134.0	0.078	3.000	136.3	114.36	103.14	12151
124	130.6	0.066	2.582	52.9	108.22	102.69	9923
125	129.4	0.028	1.140	229.9	117.05	103.46	16911
126	132.3	0.069	2.652	227.3	118.31	103.36	15207
127	135.2	0.054	2.131	136.7	115.33	103.24	11311
128	132.9	0.047	1.868	53.0	108.57	103.06	9634
129	132.9	0.039	1.541	233.0	118.00	103.11	15611
130	130.6	0.036	1.450	132.6	114.81	103.00	11233
131	128.3	0.032	1.302	52.2	107.43	102.88	11558
132	127.1	0.014	0.591	227.1	116.88	103.24	16653
133	125.9	0.009	0.403	136.8	115.14	103.08	11371
134	125.9	0.004	0.211	52.9	109.18	102.72	8244
135	130.6	0.083	3.174	228.6	118.25	103.58	15583
136	129.4	0.070	2.698	228.3	118.63	103.50	15088
137	125.9	0.061	2.366	228.4	118.55	103.53	15200
138	123.6	0.078	3.008	226.3	118.60	103.44	14918
139	129.4	0.062	2.412	226.5	118.84	103.39	14680
140	128.2	0.054	2.124	226.7	118.28	103.34	15180
141	127.1	0.065	2.512	225.6	118.80	103.30	14566
142	127.1	0.057	2.219	227.4	118.80	103.37	14743
143	128.2	0.034	1.365	226.7	118.30	103.31	15135
144	127.1	0.040	1.598	227.7	117.96	103.24	15469
145	127.1	0.032	1.308	227.3	117.70	103.15	15615
146	127.1	0.021	0.875	227.7	117.15	103.22	18344

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 30.5°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
51	391.5	0.031	1.214	129.0	112.42	104.88	17126
52	377.5	0.033	1.297	51.3	107.96	104.80	16276
53	389.0	0.029	1.134	228.2	117.00	104.86	18808
54	383.2	0.027	1.077	140.3	112.43	104.54	17787
55	387.4	0.026	1.065	52.2	108.11	104.37	13991
56	391.5	0.017	0.699	226.0	117.03	104.75	18404
57	387.4	0.015	0.640	130.5	113.27	104.60	15055
58	387.4	0.013	0.565	52.1	108.71	104.32	11879
59	384.1	0.005	0.227	229.5	118.24	103.16	14218
60	377.5	0.002	0.122	130.5	115.27	102.58	10297
61	366.8	0.000	0.611	52.6	109.67	101.45	6395
62	362.7	0.032	1.263	226.8	117.84	105.04	17732
63	383.2	0.024	0.971	232.5	118.41	104.64	16892
64	381.6	0.026	1.053	226.8	117.91	104.63	17084
65	362.7	0.021	0.865	224.1	117.78	104.47	16855
66	387.4	0.016	0.685	230.7	117.89	104.64	17430
67	358.6	0.024	0.967	225.5	117.46	104.64	17596
68	362.7	0.022	0.906	224.8	117.59	104.48	17164
69	395.6	0.011	0.479	221.1	117.99	104.37	16236
70	395.6	0.013	0.571	220.6	117.66	104.58	16869
71	403.8	0.012	0.518	224.4	117.74	104.42	16855
72	395.6	0.008	0.358	221.8	117.95	103.82	15700
73	337.5	0.027	1.089	221.9	117.83	104.68	16885
74	268.1	0.045	1.736	227.1	118.23	104.20	16195
75	254.9	0.040	1.556	129.6	114.13	104.03	12828
76	254.9	0.041	1.615	51.4	108.76	103.91	10600
77	251.4	0.035	1.399	226.4	118.41	104.31	16075
78	264.5	0.031	1.257	135.2	114.61	104.04	12793
79	244.2	0.032	1.283	51.6	108.85	103.82	10269
80	260.9	0.019	0.793	230.0	116.91	104.20	18100
81	256.1	0.017	0.702	128.8	114.01	104.19	13113
82	256.1	0.014	0.609	52.3	108.85	103.79	10350
83	260.9	0.005	0.228	230.0	117.23	102.97	16135
84	259.7	0.001	0.059	129.7	115.48	102.22	9795
85	254.9	0.002	0.083	52.5	111.35	102.76	6122
86	246.6	0.054	2.104	227.0	118.37	103.92	15721
87	270.5	0.043	1.675	226.6	118.46	103.99	15686
88	268.9	0.034	1.345	228.9	118.37	103.73	15655
89	262.1	0.040	1.582	226.5	118.29	103.73	15568
90	254.9	0.033	1.328	226.1	118.11	103.98	16020
91	260.9	0.026	1.057	226.5	117.75	103.73	16194
92	250.8	0.031	1.262	225.9	117.48	103.57	16242
93	232.3	0.031	1.225	226.7	117.28	103.93	16982
94	222.7	0.019	0.802	223.4	117.31	104.08	16890
95	269.3	0.023	0.954	233.1	117.46	104.04	17381
96	266.9	0.019	0.805	230.1	117.26	104.17	17605
97	266.9	0.014	0.583	232.9	116.51	104.05	18682
98	186.9	0.062	2.389	232.2	118.82	103.99	15672
99	186.9	0.062	2.391	133.8	114.23	103.86	12905
100	191.7	0.058	2.257	52.9	108.69	103.66	10524

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 00.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Way}	T_b	h_{TP}
1	760.0	0.013	0.552	236.4	117.50	106.41	21367
2	752.0	0.013	0.534	133.7	112.89	105.84	18972
3	741.7	0.012	0.509	55.5	108.94	105.03	14193
4	758.4	0.010	0.422	237.7	117.43	105.79	20436
5	758.1	0.009	0.378	138.0	113.15	105.30	17597
6	758.4	0.009	0.403	53.4	109.68	105.23	12026
7	749.3	0.007	0.306	237.3	118.09	105.40	18720
8	747.8	0.008	0.343	130.1	113.65	105.29	15584
9	749.3	0.007	0.333	51.4	109.21	104.91	11985
10	749.3	0.004	0.184	229.1	115.96	104.58	20136
11	761.5	0.003	0.163	128.3	113.73	104.64	14121
12	752.4	0.003	0.146	50.6	108.75	104.19	11134
13	749.3	0.013	0.551	223.7	115.75	105.98	22941
14	756.9	0.012	0.495	229.1	115.97	105.86	22715
15	735.6	0.010	0.427	223.3	115.73	105.09	21014
16	747.8	0.012	0.498	227.8	116.05	105.94	22549
17	738.7	0.009	0.393	230.3	116.29	105.52	21408
18	740.2	0.008	0.354	228.6	116.88	105.46	20031
19	747.8	0.009	0.381	230.4	116.33	105.61	21530
20	746.4	0.008	0.338	228.4	116.34	105.47	21039
21	751.8	0.006	0.256	231.1	115.47	104.59	21248
22	747.8	0.006	0.287	228.5	116.38	105.02	20119
23	749.3	0.005	0.250	230.3	116.02	105.20	21296
24	749.3	0.004	0.185	227.6	115.67	104.56	20505
25	511.9	0.023	0.913	222.2	115.65	104.81	20578
26	513.1	0.023	0.950	128.4	111.72	104.63	18170
27	522.4	0.023	0.930	50.6	107.63	104.21	14892
28	520.9	0.020	0.811	226.9	114.96	104.36	21473
29	517.9	0.019	0.792	138.2	111.24	104.30	18560
30	517.9	0.018	0.768	51.7	107.73	104.14	14460
31	522.4	0.013	0.545	228.4	114.79	104.00	21205
32	520.9	0.012	0.524	128.4	111.56	103.78	16549
33	523.9	0.010	0.452	51.8	108.18	103.84	11946
34	522.4	0.005	0.226	229.9	114.47	103.77	21535
35	519.4	0.003	0.161	129.6	112.41	103.64	14797
36	522.4	0.003	0.130	51.7	108.04	103.15	10600
37	520.9	0.022	0.910	230.1	114.73	104.55	22663
38	520.9	0.019	0.800	227.8	114.76	104.28	21800
39	520.9	0.017	0.715	225.6	115.17	104.39	20968
40	517.9	0.020	0.841	229.1	113.82	104.36	24228
41	510.4	0.018	0.736	227.9	116.20	104.25	19146
42	507.8	0.015	0.648	227.1	116.67	104.57	18550
43	504.4	0.018	0.750	227.4	116.01	104.70	20157
44	505.9	0.016	0.664	230.4	116.09	104.52	19962
45	504.4	0.010	0.458	225.2	116.42	104.09	18325
46	502.9	0.012	0.508	227.6	115.73	104.23	19842
47	507.4	0.009	0.417	227.8	115.80	104.19	19659
48	502.9	0.007	0.321	229.3	115.88	103.91	19210
49	367.7	0.033	1.323	229.7	116.95	104.27	18173
50	376.7	0.032	1.275	130.2	112.19	104.07	16110

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 00.0°

S.NO.	G	x	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
51	370.1	0.029	1.185	50.8	107.40	103.34	12586
52	373.4	0.025	1.040	228.8	116.28	103.62	18126
53	376.7	0.025	1.012	129.8	112.01	103.71	15703
54	375.0	0.024	0.988	51.1	107.40	103.58	13217
55	373.4	0.015	0.634	228.5	116.66	103.75	17761
56	376.7	0.014	0.593	129.5	112.75	103.54	14095
57	378.3	0.013	0.555	51.8	108.17	103.28	10631
58	375.0	0.006	0.265	223.7	118.71	103.41	14626
59	373.4	0.004	0.192	128.2	113.61	103.51	12702
60	375.0	0.001	0.075	51.4	108.86	102.79	8466
61	380.0	0.031	1.213	229.0	116.69	105.19	19842
62	371.7	0.025	1.006	229.4	116.86	103.67	17456
63	373.4	0.021	0.881	229.0	117.33	103.62	16768
64	371.7	0.027	1.085	227.5	116.21	103.88	18497
65	373.4	0.021	0.855	227.9	116.99	103.88	17433
66	373.4	0.017	0.730	228.7	117.30	103.76	16949
67	368.5	0.020	0.837	226.4	115.10	103.17	19027
68	371.7	0.019	0.781	227.9	115.17	103.68	19906
69	376.7	0.012	0.522	228.6	116.75	103.45	17365
70	375.0	0.014	0.614	228.6	114.38	103.37	19970
71	373.4	0.012	0.531	226.6	114.94	103.41	19737
72	371.7	0.008	0.367	229.5	115.07	103.04	19147
73	252.6	0.047	1.868	226.5	118.34	103.34	15127
74	246.6	0.047	1.847	130.6	113.47	103.15	12748
75	247.8	0.043	1.716	51.9	108.23	103.16	10266
76	244.2	0.036	1.453	227.1	118.73	103.07	14515
77	246.6	0.033	1.342	130.6	114.62	102.82	12109
78	248.4	0.032	1.306	51.9	108.07	102.89	10045
79	246.8	0.020	0.853	224.8	118.35	102.90	14555
80	245.4	0.019	0.813	133.4	113.77	103.26	12689
81	249.0	0.018	0.762	51.5	107.56	102.99	11270
82	246.0	0.005	0.239	227.9	117.99	102.61	15050
83	240.0	0.003	0.167	131.0	115.86	102.88	10110
84	241.2	0.000	0.029	50.6	109.00	102.25	7502
85	246.0	0.045	1.773	226.9	118.22	103.15	15075
86	245.4	0.038	1.523	229.8	118.69	103.12	15165
87	243.0	0.032	1.298	228.8	118.76	103.13	14638
88	244.2	0.042	1.661	228.0	118.02	103.14	15354
89	243.6	0.032	1.289	228.3	118.59	103.01	14666
90	241.2	0.025	1.051	226.6	118.64	102.53	14073
91	243.0	0.034	1.343	226.7	117.79	103.66	15412
92	244.2	0.029	1.190	229.1	118.16	102.87	15007
93	244.2	0.017	0.732	229.6	118.50	102.89	14717
94	243.6	0.021	0.891	224.3	117.73	102.91	15154
95	244.2	0.017	0.726	227.6	117.60	102.77	15366
96	245.4	0.012	0.518	225.8	117.59	103.00	15486
97	185.4	0.064	2.483	224.7	118.72	103.01	14308
98	183.8	0.063	2.470	138.4	113.95	103.06	12726
99	181.6	0.061	2.375	52.0	108.00	102.89	10214
100	179.2	0.052	2.046	224.9	118.88	103.10	14254

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HEAT TRANSFER DATA

ANGLE OF INCLINATION = 00.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
101	178.6	0.049	1.948	128.1	113.83	103.16	12000
102	167.6	0.049	1.955	51.4	107.67	102.91	10848
103	195.2	0.047	1.865	228.4	118.94	103.04	14368
104	193.5	0.025	1.030	130.8	114.36	103.06	11600
105	198.3	0.024	0.995	52.0	107.60	102.91	11107
106	193.5	0.006	0.289	222.2	118.26	102.85	14424
107	192.9	0.002	0.118	125.1	112.58	102.19	12112
108	192.9	0.000	1.652	49.6	107.98	102.05	8407
109	178.6	0.069	2.680	221.2	118.63	103.25	14384
110	180.4	0.061	2.373	222.7	118.68	103.36	14551
111	178.6	0.054	2.111	221.6	118.75	103.41	14463
112	179.2	0.060	2.354	222.1	118.36	103.27	14719
113	178.0	0.046	1.834	219.7	118.41	103.22	14467
114	177.5	0.038	1.534	219.6	118.86	103.12	13963
115	186.9	0.042	1.686	218.4	118.15	103.02	14433
116	187.5	0.037	1.498	221.1	118.36	103.08	14476
117	183.4	0.021	0.884	218.0	118.00	102.88	14424
118	183.4	0.028	1.147	219.5	117.82	103.14	14951
119	182.2	0.022	0.937	216.4	117.15	102.92	15231
120	181.6	0.014	0.591	218.0	116.77	102.88	15709
121	128.2	0.097	3.737	222.6	118.74	103.03	14184
122	128.2	0.091	3.544	126.7	113.31	102.71	11950
123	130.6	0.087	3.393	50.1	107.36	102.74	10887
124	130.0	0.070	2.730	223.4	118.43	102.68	14200
125	129.4	0.066	2.590	126.7	113.22	102.51	11837
126	130.0	0.062	2.409	50.0	107.96	102.99	10109
127	123.6	0.037	1.497	223.3	117.79	102.78	14881
128	126.5	0.031	1.268	125.9	114.65	102.74	10579
129	126.5	0.028	1.140	49.2	108.70	102.45	7871
130	124.8	0.009	0.410	220.1	117.09	102.75	15371
131	125.9	0.006	0.264	126.2	114.76	102.61	10421
132	124.8	0.003	0.141	49.8	109.65	102.68	7157
133	125.3	0.102	3.948	222.3	118.11	103.00	14718
134	125.3	0.088	3.404	221.4	118.01	102.95	14714
135	125.3	0.075	2.911	223.9	118.33	102.69	14324
136	124.5	0.088	3.411	222.8	117.78	102.97	15061
137	124.8	0.066	2.587	222.0	118.73	102.58	14111
138	124.8	0.054	2.109	223.0	118.76	102.89	14062
139	121.9	0.055	2.161	225.3	119.82	103.01	13406
140	126.5	0.046	1.840	224.3	119.81	103.02	13370
141	125.9	0.025	1.026	224.5	118.56	103.11	14535
142	125.9	0.033	1.330	225.1	118.87	103.02	14201
143	125.9	0.025	1.049	223.4	118.75	103.08	14254
144	125.9	0.015	0.665	224.3	118.24	102.99	14715
145	105.1	0.128	4.967	218.3	121.92	103.10	11651
146	104.5	0.122	4.730	125.6	115.54	103.07	10112
147	103.3	0.117	4.544	49.8	108.16	102.80	9305
148	103.9	0.094	3.611	219.2	122.35	103.15	11489
149	103.9	0.087	3.370	125.6	115.65	102.96	9920
150	103.9	0.083	3.204	50.0	108.19	102.84	9350

Contd....

HEAT TRANSFER DATA

ANGLE OF INCLINATION = 00.0°

S.NO.	G	X	$1/X_{tt}$	q/A	T_{Wav}	T_b	h_{TP}
151	104.5	0.045	1.792	209.6	119.39	103.14	12907
152	104.5	0.041	1.638	128.2	116.34	103.01	9614
153	104.5	0.039	1.553	51.7	109.78	102.81	7421
154	103.9	0.015	0.637	211.6	117.01	103.00	15119
155	102.8	0.005	0.250	51.1	109.68	102.87	7518
156	108.3	0.107	4.127	217.5	118.29	102.98	14212
157	107.0	0.095	3.660	217.0	119.00	103.04	13602
158	107.2	0.081	3.120	217.0	119.94	103.17	12943
159	107.4	0.097	3.767	216.7	118.38	102.98	14069
160	107.4	0.076	2.944	216.7	119.53	103.14	13220
161	107.4	0.082	3.174	216.8	119.26	103.06	13369
162	107.4	0.071	2.762	216.8	118.83	102.91	13624
163	106.3	0.061	2.393	216.3	118.96	102.83	13418
164	107.4	0.034	1.359	216.3	118.87	103.08	13710
165	107.4	0.050	1.958	216.7	119.01	103.06	13588
166	107.4	0.040	1.612	216.4	118.88	103.00	13635
167	107.4	0.025	1.049	215.8	118.09	102.87	14184

APPENDIX C

PRESSURE DROP DATA

G — mass velocity, kg/m^{2}s

x_i = mass vapor quality at the inlet of pre-evaporator E3

x_o = mass vapor quality at the outlet of pre-evaporator E3

$X_{tt,av}$ Lockhart-Martinelli parameter (averaged over pre-evaporator, E3)

q/A heat flux, kW/m^2

TPD · two-phase flow total pressure drop, Pa

PRESSURE DROP DATA   ANGLE OF INCLINATION = 90.0°

S.NO.	G	x_i	x_o	$X_{tt,av}$	α/A	TPD
1	758.4	0.009	0.016	1.949	92.9	4378
2	734.1	0.005	0.011	2.868	67.3	3748
3	761.5	0.003	0.007	4.274	31.2	3520
4	756.9	0.002	0.004	7.349	0.0	3655
5	756.9	0.006	0.012	2.540	74.7	3824
6	756.9	0.006	0.010	2.842	32.7	3701
7	741.7	0.008	0.010	2.485	0.0	3748
8	773.6	0.003	0.010	3.717	89.5	3649
9	758.4	0.004	0.008	3.786	31.9	3555
10	753.9	0.005	0.006	3.941	0.0	3742
11	761.5	0.002	0.003	8.418	0.0	3742
12	750.8	0.003	0.010	3.677	86.3	3841
13	744.0	0.005	0.013	2.722	92.4	4162
14	753.9	0.005	0.013	2.708	92.5	4261
15	741.7	0.006	0.014	2.425	92.6	4250
16	759.7	0.003	0.010	4.035	68.3	3649
17	761.5	0.003	0.009	3.870	67.8	3666
18	761.5	0.004	0.010	3.383	68.3	3678
19	761.5	0.001	0.005	8.065	34.7	3509
20	753.9	0.002	0.005	6.517	35.3	3503
21	750.8	0.002	0.006	5.898	34.7	3480
22	755.4	0.002	0.004	6.919	0.0	3742
23	743.2	0.011	0.012	3.032	63.6	3911
24	749.3	0.006	0.009	3.070	31.5	3602
25	749.3	0.006	0.008	3.150	0.0	3602
26	749.3	0.001	0.009	5.542	90.1	3812
27	749.3	0.003	0.006	4.900	33.9	3555
28	746.3	0.003	0.005	4.970	0.0	3666
29	752.4	0.009	0.017	1.877	91.6	4477
30	749.3	0.009	0.016	1.902	90.7	4627
31	752.4	0.009	0.017	1.820	92.0	4646
32	752.4	0.006	0.012	2.603	66.9	3684
33	747.8	0.006	0.012	2.546	65.4	3783
34	747.8	0.006	0.012	2.472	66.4	4146
35	755.4	0.003	0.007	4.484	30.2	3462
36	753.9	0.004	0.008	3.776	29.0	3485
37	753.9	0.003	0.006	4.625	28.9	3485
38	738.7	0.002	0.004	7.017	0.0	3730
39	756.9	0.006	0.012	2.540	74.7	3824
40	505.9	0.015	0.025	1.209	91.4	3293
41	510.4	0.011	0.019	1.593	68.3	3372
42	504.4	0.005	0.010	2.935	31.6	3305
43	499.9	0.002	0.003	8.136	0.0	3550
44	499.9	0.016	0.024	1.221	68.4	3202
45	499.9	0.016	0.021	1.269	31.2	3095
46	508.9	0.018	0.019	1.277	0.0	3217
47	514.9	0.012	0.021	1.464	88.3	3445
48	505.9	0.013	0.017	1.541	32.6	3112
49	508.9	0.014	0.015	1.607	0.0	2990
50	505.9	0.007	0.017	2.029	90.0	3223

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 90.0°

S.NO.	G	x_1	x_o	$X_{tt,av}$	α/A	TPD
51	520.9	0.007	0.015	2.133	64.2	3263
52	522.4	0.008	0.010	2.413	0.0	3074
53	519.4	0.003	0.013	3.081	88.9	3491
54	511.2	0.014	0.023	1.326	86.7	3135
55	507.4	0.015	0.025	1.226	88.8	3135
56	511.9	0.016	0.025	1.195	86.5	3001
57	505.2	0.016	0.025	1.185	84.7	2954
58	509.7	0.010	0.018	1.704	65.8	3258
59	511.9	0.012	0.019	1.550	63.9	2844
60	489.4	0.013	0.020	1.469	63.8	2780
61	510.4	0.012	0.019	1.543	64.2	2931
62	514.9	0.005	0.010	2.886	32.3	3485
63	511.9	0.007	0.011	2.479	33.1	3439
64	513.4	0.006	0.010	2.828	33.4	3462
65	511.9	0.006	0.011	2.660	33.0	3445
66	508.9	0.001	0.003	10.720	0.0	3550
67	505.9	0.001	0.004	7.312	0.0	3520
68	508.2	0.003	0.004	5.928	0.0	3404
69	505.9	0.003	0.004	5.831	0.0	3357
70	507.4	0.016	0.023	1.249	69.0	2931
71	510.4	0.017	0.021	1.267	33.3	3036
72	512.7	0.018	0.019	1.281	0.0	3135
73	511.9	0.011	0.020	1.544	91.5	3065
74	510.4	0.012	0.016	1.630	33.4	2832
75	510.4	0.013	0.014	1.582	0.0	2855
76	511.9	0.006	0.016	2.260	92.7	3550
77	510.4	0.006	0.014	2.323	67.3	3456
78	510.4	0.008	0.009	2.639	0.0	3083
79	510.4	0.002	0.010	4.035	69.5	3410
80	510.4	0.002	0.007	4.763	33.5	3275
81	507.4	0.015	0.025	1.198	91.2	3322
82	508.9	0.014	0.023	1.275	83.8	3275
83	508.9	0.015	0.024	1.240	82.2	3299
84	510.4	0.010	0.018	1.681	68.4	3421
85	508.9	0.011	0.019	1.597	68.2	3392
86	510.4	0.011	0.019	1.592	68.8	3398
87	499.9	0.006	0.010	2.873	31.4	3322
88	502.9	0.006	0.010	2.736	32.1	3380
89	504.4	0.006	0.011	2.660	32.6	3351
90	501.4	0.002	0.003	8.021	0.0	3550
91	499.9	0.002	0.004	7.516	0.0	3550
92	501.4	0.003	0.005	5.535	0.0	3550
93	378.3	0.021	0.033	0.903	89.0	2482
94	375.0	0.016	0.025	1.180	62.2	2383
95	371.7	0.011	0.016	1.646	31.2	2272
96	380.0	0.024	0.033	0.864	64.6	2640
97	381.6	0.025	0.030	0.889	31.5	2704
98	383.2	0.025	0.027	0.922	0.0	2686
99	381.6	0.017	0.028	1.084	84.9	2389
100	380.0	0.017	0.022	1.190	31.2	2336
101	381.2	0.017	0.018	1.298	0.0	2301
102	383.2	0.009	0.021	1.602	84.1	2803

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 90.0°

S.NO.	G	X_1	X_o	$X_{tt,av}$	α/A	TPD
103	383.2	0.009	0.019	1.691	66.2	2745
104	383.2	0.010	0.011	2.137	0.0	2535
105	380.0	0.001	0.013	4.410	85.4	3013
106	380.0	0.001	0.011	5.030	65.0	3170
107	380.0	0.023	0.035	0.849	90.1	2680
108	379.1	0.023	0.034	0.864	83.4	2575
109	379.1	0.024	0.035	0.844	83.9	2622
110	378.3	0.023	0.035	0.851	84.2	2657
111	378.3	0.018	0.027	1.085	66.8	2365
112	378.3	0.018	0.027	1.074	63.3	2342
113	378.3	0.018	0.027	1.060	63.3	2354
114	378.3	0.018	0.027	1.056	64.3	2354
115	381.6	0.011	0.016	1.694	34.2	2278
116	381.6	0.011	0.016	1.750	32.1	2190
117	381.6	0.010	0.015	1.800	32.2	2172
118	378.3	0.004	0.006	4.139	0.0	2955
119	380.0	0.001	0.003	10.140	0.0	3462
120	379.2	0.001	0.003	10.330	0.0	3462
121	380.0	0.001	0.003	10.990	0.0	3462
122	380.0	0.024	0.034	0.857	70.1	2669
123	378.3	0.025	0.030	0.891	34.5	2686
124	378.3	0.024	0.026	0.956	0.0	2791
125	380.0	0.017	0.029	1.079	91.9	2453
126	378.3	0.017	0.023	1.184	32.7	2406
127	379.1	0.018	0.019	1.274	0.0	2424
128	394.8	0.008	0.020	1.716	89.6	2482
129	379.1	0.010	0.019	1.660	64.5	2324
130	378.3	0.010	0.011	2.036	0.0	2253
131	378.3	0.002	0.011	3.974	62.7	3083
132	378.3	0.002	0.007	4.909	31.7	3235
133	376.7	0.022	0.034	0.872	86.9	2435
134	371.7	0.022	0.034	0.876	85.8	2447
135	375.0	0.022	0.034	0.881	87.1	2476
136	371.7	0.016	0.024	1.195	59.8	2289
137	373.4	0.016	0.024	1.175	60.3	2301
138	373.4	0.015	0.024	1.223	59.5	2330
139	371.7	0.012	0.017	1.580	30.7	2272
140	380.0	0.010	0.015	1.766	30.7	2319
141	378.3	0.011	0.015	1.747	30.8	2377
142	370.1	0.003	0.005	4.989	0.0	3474
143	380.0	0.003	0.005	4.937	0.0	3480
144	383.2	0.003	0.005	4.810	0.0	3480
145	381.6	0.003	0.005	4.852	0.0	3480
146	380.0	0.001	0.007	6.250	32.5	3310
147	252.6	0.033	0.049	0.608	86.0	1432
148	250.8	0.032	0.048	0.611	84.6	1388
149	253.1	0.023	0.035	0.829	64.8	1304
150	252.8	0.001	0.003	11.042	0.0	3404

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 90.0°

S.NO.	G	X_i	X_o	$X_{tt,av}$	q/A	TPD
151	254.9	0.033	0.045	0.623	62.8	1362
152	255.5	0.034	0.040	0.653	31.1	1385
153	256.7	0.034	0.035	0.698	0.0	1438
154	260.3	0.023	0.040	0.784	90.0	1304
155	260.9	0.024	0.031	0.868	32.7	1304
156	250.8	0.025	0.026	0.910	0.0	1327
157	252.8	0.014	0.014	0.587	0.0	1438
158	251.4	0.001	0.018	3.566	87.4	2033
159	252.0	0.001	0.008	5.797	31.4	2616
160	270.1	0.003	0.016	2.749	90.0	3065
161	244.2	0.034	0.051	0.588	88.9	1461
162	254.4	0.036	0.053	0.557	88.4	1438
163	254.4	0.036	0.052	0.564	88.5	1461
164	254.9	0.036	0.052	0.563	88.8	1473
165	253.7	0.023	0.035	0.838	64.1	1286
166	254.9	0.026	0.038	0.763	66.3	1274
167	255.5	0.025	0.038	0.770	66.6	1269
168	255.5	0.025	0.038	0.769	66.5	1280
169	253.8	0.012	0.018	1.509	32.5	1245
170	257.3	0.013	0.019	1.424	32.1	1152
171	256.7	0.013	0.019	1.431	32.4	1152
172	257.9	0.013	0.019	1.422	32.1	1152
173	251.4	0.037	0.049	0.576	63.3	1344
174	254.9	0.034	0.041	0.648	30.6	1385
175	245.9	0.035	0.035	0.688	0.0	1432
176	257.3	0.023	0.039	0.792	85.9	1304
177	253.8	0.023	0.030	0.893	31.4	1257
178	254.4	0.023	0.024	0.994	0.0	1309
179	254.9	0.007	0.012	1.198	83.9	1222
180	254.9	0.012	0.024	1.300	62.1	1170
181	257.9	0.015	0.016	1.431	0.0	1304
182	253.8	0.002	0.019	3.195	88.8	1799
183	252.6	0.032	0.048	0.611	84.9	1397
184	253.8	0.032	0.048	0.613	85.1	1461
185	253.1	0.023	0.035	0.836	64.2	1304
186	252.0	0.023	0.035	0.832	63.5	1309
187	253.1	0.023	0.034	0.845	62.6	1309
188	253.1	0.013	0.019	1.450	31.6	1263
189	253.5	0.013	0.019	1.419	32.0	1257
190	254.7	0.013	0.019	1.418	32.3	1274
191	254.4	0.013	0.020	1.391	32.4	1263
192	253.8	0.001	0.003	9.864	0.0	3404
193	253.8	0.006	0.007	3.039	0.0	1706
194	251.4	0.014	0.031	1.098	90.9	1239
195	251.2	0.013	0.026	1.207	64.2	1175
196	188.7	0.045	0.067	0.447	88.7	1187
197	191.7	0.029	0.045	0.655	65.7	1047
198	194.1	0.042	0.057	0.499	62.1	1053
199	189.0	0.046	0.055	0.486	33.2	1050
200	189.3	0.047	0.047	0.516	0.0	1070

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 90.0°

S.NO.	G	x_i	x_o	$X_{tt,av}$	Q/A	TPD
201	189.3	0.031	0.053	0.587	89.2	1058
202	189.3	0.031	0.040	0.676	32.2	1023
203	189.3	0.032	0.033	0.730	0.0	1023
204	189.7	0.017	0.038	0.979	86.7	918
205	189.4	0.017	0.032	1.049	63.6	918
206	189.3	0.017	0.017	1.325	0.0	1088
207	188.1	0.005	0.021	2.619	63.1	1752
208	189.3	0.003	0.011	3.710	79.9	2126
209	189.9	0.042	0.062	0.478	83.5	1129
210	188.1	0.044	0.066	0.459	88.9	1193
211	188.1	0.044	0.067	0.451	89.6	1164
212	188.1	0.044	0.066	0.451	88.5	1175
213	190.5	0.030	0.045	0.653	62.1	994
214	194.1	0.025	0.041	0.747	66.7	1023
215	193.7	0.025	0.041	0.734	67.2	988
216	192.9	0.025	0.042	0.726	67.1	1000
217	189.0	0.015	0.030	1.074	61.5	988
218	189.3	0.010	0.019	1.561	34.0	1199
219	189.3	0.012	0.020	1.428	34.0	1134
220	189.3	0.012	0.021	1.412	33.7	1134
221	188.7	0.003	0.004	5.861	0.0	1899
222	183.4	0.044	0.061	0.475	68.1	1111
223	189.3	0.042	0.051	0.526	32.4	1164
224	189.3	0.042	0.043	0.569	0.0	1175
225	190.5	0.030	0.052	0.602	91.1	1169
226	186.9	0.028	0.036	0.744	32.7	1041
227	186.9	0.030	0.030	0.792	0.0	1099
228	188.1	0.016	0.038	0.906	89.1	1035
229	189.1	0.015	0.031	1.051	64.8	977
230	188.1	0.015	0.016	1.471	0.0	1234
231	188.1	0.045	0.067	0.448	89.0	1198
232	186.9	0.044	0.066	0.451	88.4	1187
233	186.3	0.045	0.067	0.449	88.9	1175
234	191.7	0.030	0.046	0.649	65.5	1035
235	191.1	0.030	0.046	0.651	65.3	1035
236	191.1	0.030	0.046	0.650	65.3	1035
237	193.5	0.012	0.020	1.401	31.3	1152
238	190.5	0.013	0.021	1.364	31.2	1129
239	191.1	0.013	0.021	1.088	30.9	1158
240	191.1	0.013	0.021	1.355	31.2	1158
241	188.7	0.002	0.004	6.456	0.0	3380
242	123.6	0.067	0.099	0.305	85.1	843
243	127.1	0.039	0.061	0.507	61.2	790
244	128.3	0.023	0.035	0.833	32.0	755
245	127.7	0.063	0.087	0.334	65.8	844
246	127.3	0.064	0.075	0.356	31.4	819
247	127.7	0.058	0.058	0.447	0.0	808
248	127.7	0.040	0.072	0.452	87.9	854
249	127.7	0.040	0.052	0.528	31.3	819
250	127.7	0.041	0.041	0.588	0.0	907

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 90.0°

S.NO.	G	x_i	x_o	$X_{tt,av}$	q/A	TPD
251	128.9	0.021	0.053	0.773	87.7	808
252	127.1	0.021	0.044	0.821	64.0	773
253	126.9	0.021	0.021	1.103	0.0	1047
254	125.0	0.005	0.029	2.545	66.7	1053
255	126.5	0.004	0.016	2.996	31.8	1216
256	125.5	0.063	0.097	0.318	92.7	878
257	125.9	0.065	0.098	0.310	88.8	942
258	125.9	0.065	0.098	0.310	88.4	953
259	124.8	0.066	0.099	0.308	88.3	953
260	124.8	0.042	0.067	0.456	67.8	813
261	124.8	0.047	0.071	0.427	65.3	848
262	125.9	0.047	0.071	0.424	65.7	848
263	125.9	0.047	0.071	0.424	65.2	848
264	122.4	0.019	0.031	0.955	32.0	860
265	126.5	0.025	0.028	0.760	33.2	825
266	125.9	0.026	0.039	0.738	33.3	825
267	126.9	0.026	0.039	0.733	33.4	825
268	125.5	0.005	0.005	4.022	0.0	1379
269	127.3	0.064	0.089	0.328	69.0	767
270	128.9	0.063	0.075	0.360	32.8	767
271	130.0	0.063	0.063	0.390	0.0	778
272	126.9	0.043	0.076	0.427	90.6	883
273	126.5	0.043	0.056	0.492	34.7	755
274	125.7	0.042	0.043	0.566	0.0	872
275	123.3	0.020	0.054	0.691	88.8	918
276	122.7	0.020	0.045	0.761	63.9	907
277	126.4	0.022	0.022	1.049	0.0	1041
278	123.0	0.065	0.097	0.312	84.8	825
279	125.9	0.061	0.092	0.329	84.1	825
280	126.5	0.059	0.090	0.334	83.8	843
281	127.7	0.039	0.061	0.496	61.4	755
282	128.2	0.038	0.060	0.503	61.4	778
283	127.7	0.039	0.061	0.494	61.1	767
284	128.2	0.023	0.035	0.813	32.0	755
285	128.2	0.025	0.036	0.780	32.5	761
286	128.2	0.024	0.036	0.786	32.2	761
287	125.9	0.025	0.036	0.783	31.9	761

PRESSURE DROP DATA ANGLE OF INCLINATION = 67.5°

S.NO.	G	x_i	x_o	$X_{tt,av}$	α/A	TPD
1	750.8	0.008	0.016	1.997	94.5	4234
2	760.0	0.003	0.009	4.053	68.3	3546
3	760.0	0.002	0.005	6.260	34.2	3301
4	755.4	0.008	0.014	2.142	70.3	3908
5	755.4	0.008	0.012	2.295	33.5	3791
6	756.2	0.009	0.011	2.256	0.0	3680
7	750.8	0.003	0.010	3.563	90.0	3604
8	760.0	0.004	0.008	3.629	32.1	3388
9	756.9	0.004	0.006	4.056	0.0	3453
10	760.0	0.000	0.007	11.333	87.3	3482
11	772.1	0.001	0.006	7.741	65.2	3447
12	749.3	0.002	0.004	6.899	0.0	3447
13	761.5	0.006	0.013	2.413	93.4	3797
14	756.9	0.007	0.014	2.253	94.8	3995
15	750.8	0.008	0.015	2.077	93.9	4118
16	758.4	0.004	0.010	3.310	68.9	3639
17	753.9	0.005	0.010	3.074	67.5	3727
18	761.5	0.005	0.011	2.956	68.7	3797
19	760.0	0.002	0.005	6.078	34.2	3313
20	763.0	0.002	0.006	5.539	34.3	3313
21	764.5	0.002	0.006	5.328	34.3	3313
22	502.9	0.014	0.024	1.256	87.1	3173
23	499.9	0.010	0.018	1.676	67.4	3219
24	499.9	0.006	0.010	2.744	32.3	3313
25	499.9	0.015	0.022	1.271	67.5	3149
26	499.9	0.015	0.020	1.347	33.4	3015
27	502.9	0.017	0.018	1.327	0.0	2939
28	510.4	0.009	0.019	1.676	90.2	3534
29	511.9	0.010	0.014	1.878	33.4	3260
30	513.4	0.011	0.012	1.968	0.0	3068
31	493.9	0.004	0.015	2.599	100.0	3441
32	499.9	0.004	0.011	2.998	63.6	3406
33	499.9	0.006	0.007	3.363	0.0	3196
34	495.4	0.014	0.024	1.256	86.5	3249
35	495.4	0.014	0.024	1.251	86.2	3249
36	490.9	0.014	0.023	1.272	83.3	3149
37	511.9	0.010	0.017	1.744	64.9	3377
38	507.4	0.010	0.018	1.655	66.7	3342
39	505.9	0.011	0.018	1.630	67.0	3289
40	504.4	0.006	0.010	2.809	32.4	3406
41	502.9	0.005	0.009	3.087	32.0	3424
42	499.9	0.005	0.010	2.958	31.5	3418
43	499.9	0.001	0.003	11.241	0.0	3289
44	500.7	0.000	0.005	13.781	0.0	3295
45	503.7	0.015	0.025	1.205	90.0	3164
46	495.4	0.016	0.026	1.140	90.2	3144
47	495.4	0.016	0.026	1.135	90.0	3144
48	496.9	0.016	0.026	1.128	90.1	3144
49	504.4	0.011	0.019	1.539	67.1	3272
50	507.4	0.012	0.019	1.523	67.4	3231

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 67.5°

S.NO.	G	X_i	X_o	$X_{tt,av}$	α/A	TPD
51	508.2	0.012	0.020	1.492	67.7	3214
52	505.9	0.012	0.020	1.471	67.9	3254
53	506.7	0.007	0.011	2.528	33.3	3272
54	507.4	0.007	0.011	2.535	33.4	3243
55	507.4	0.007	0.011	2.474	33.3	3295
56	508.9	0.007	0.011	2.456	33.2	3330
57	507.4	0.001	0.003	8.816	0.0	3295
58	507.5	0.001	0.003	9.013	0.0	3301
59	508.9	0.001	0.003	8.817	0.0	3289
60	508.9	0.002	0.003	8.097	0.0	3289
61	507.4	0.016	0.024	1.195	70.1	3179
62	505.9	0.017	0.021	1.249	33.4	3009
63	502.9	0.017	0.019	1.294	0.0	2904
64	503.7	0.011	0.021	1.486	92.2	3470
65	508.2	0.012	0.016	1.633	33.7	3155
66	501.4	0.012	0.014	1.759	0.0	3004
67	504.4	0.005	0.015	2.387	87.0	3429
68	507.4	0.006	0.013	2.428	65.3	3354
69	504.4	0.006	0.008	3.013	0.0	3144
70	487.9	0.003	0.012	3.384	88.9	3284
71	504.4	0.002	0.010	4.029	67.3	3278
72	502.9	0.002	0.007	4.693	32.0	3214
73	388.2	0.022	0.033	0.882	86.8	2549
74	380.0	0.020	0.032	0.933	89.3	2466
75	378.3	0.015	0.024	1.234	65.8	2367
76	378.3	0.008	0.013	2.131	32.6	2875
77	383.2	0.002	0.003	7.425	0.0	3219
78	383.2	0.020	0.029	0.968	69.5	2502
79	380.0	0.021	0.026	1.021	33.0	2379
80	375.0	0.021	0.022	1.080	0.0	2379
81	370.1	0.013	0.026	1.228	89.8	2379
82	375.0	0.016	0.025	1.172	66.4	2333
83	380.0	0.009	0.021	1.581	90.2	2799
84	380.0	0.009	0.019	1.660	66.7	2694
85	381.6	0.010	0.011	2.064	0.0	2420
86	380.0	0.004	0.015	2.606	86.1	3015
87	380.0	0.003	0.013	3.000	66.7	3044
88	378.3	0.004	0.009	3.423	31.6	3144
89	380.0	0.020	0.032	0.933	89.3	2426
90	388.2	0.021	0.033	0.890	86.8	2549
91	388.2	0.022	0.033	0.887	85.7	2578
92	384.9	0.008	0.016	1.884	61.3	2385
93	384.9	0.017	0.025	1.118	61.4	2420
94	386.5	0.018	0.026	1.082	63.2	2473
95	386.5	0.011	0.016	1.715	35.2	2362
96	386.5	0.011	0.016	1.719	34.5	2344
97	379.8	0.010	0.016	1.735	33.7	2333
98	378.3	0.003	0.004	6.006	0.0	3132
99	380.0	0.003	0.005	4.771	0.0	3132
100	380.0	0.003	0.005	4.875	0.0	3085
101	378.3	0.017	0.018	1.326	0.0	2257
102	375.0	0.023	0.035	0.834	88.8	2467

Contd....

PRESSURE DROP DATA

ANGLE OF INCLINATION = 67.5°

S.NO.	G	X_i	X_o	$X_{tt,av}$	a/A	TPD
103	378.3	0.023	0.035	0.831	88.6	2479
104	378.3	0.024	0.036	0.821	89.9	2554
105	377.5	0.024	0.036	0.816	89.0	2554
106	380.0	0.017	0.025	1.126	65.1	2268
107	379.1	0.017	0.026	1.112	64.3	2268
108	373.4	0.017	0.026	1.093	63.1	2257
109	379.1	0.016	0.024	1.179	64.6	2303
110	371.7	0.008	0.014	2.038	31.0	2875
111	375.0	0.008	0.013	2.076	31.2	2893
112	371.7	0.009	0.014	1.948	0.0	2648
113	380.0	0.009	0.014	1.962	31.3	2729
114	371.7	0.004	0.005	4.527	0.0	3225
115	380.0	0.003	0.005	5.007	0.0	3225
116	383.2	0.003	0.005	4.897	0.0	3225
117	381.6	0.003	0.005	4.832	0.0	3225
118	383.2	0.023	0.032	0.868	66.9	2473
119	381.6	0.024	0.029	0.898	33.1	2426
120	383.2	0.024	0.025	0.956	0.0	2426
121	380.0	0.017	0.028	1.067	90.3	2403
122	380.0	0.017	0.022	1.194	32.9	2274
123	380.8	0.017	0.018	1.309	0.0	2233
124	380.0	0.002	0.015	3.221	90.9	2957
125	380.0	0.003	0.012	3.400	68.1	3009
126	380.0	0.002	0.008	4.348	32.1	3179
127	323.2	0.009	0.010	2.297	0.0	2531
128	251.4	0.035	0.051	0.570	83.1	1382
129	257.3	0.023	0.034	0.834	61.3	1283
130	249.0	0.016	0.023	1.182	35.1	1311
131	251.4	0.034	0.047	0.596	69.6	1213
132	254.4	0.034	0.040	0.648	31.8	1183
133	253.5	0.033	0.033	0.719	0.0	1195
134	253.8	0.024	0.041	0.743	87.4	1291
135	253.8	0.024	0.031	0.858	31.4	1183
136	253.8	0.025	0.025	0.929	0.0	1230
137	244.8	0.014	0.033	1.061	99.0	1306
138	253.1	0.014	0.027	1.156	71.8	1323
139	252.6	0.014	0.015	1.531	0.0	1452
140	253.1	0.000	0.019	5.281	95.9	2041
141	253.1	0.001	0.015	4.323	72.4	2134
142	252.0	0.000	0.008	7.710	34.3	2566
143	249.0	0.035	0.051	0.571	85.4	1393
144	254.9	0.049	0.051	0.487	85.2	1413
145	257.3	0.033	0.049	0.596	83.3	1393
146	256.7	0.025	0.038	0.763	64.5	1294
147	253.1	0.025	0.038	0.756	67.7	1195
148	256.1	0.026	0.038	0.750	68.3	1253
149	258.5	0.015	0.021	1.276	34.9	1265
150	250.2	0.016	0.023	1.210	35.1	1224

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 67.5°

S.NO.	G	x_i	x_o	$X_{tt,av}$	q/A	TPD
151	249.0	0.016	0.023	1.204	35.0	1253
152	254.9	0.035	0.051	0.567	87.9	1434
153	252.6	0.036	0.052	0.555	87.2	1364
154	252.0	0.036	0.052	0.560	87.1	1417
155	252.0	0.034	0.050	0.583	86.1	1358
156	246.6	0.025	0.037	0.771	63.7	1207
157	250.8	0.025	0.037	0.781	64.0	1218
158	251.4	0.025	0.037	0.776	64.0	1259
159	250.2	0.025	0.038	0.761	64.3	1230
160	249.0	0.016	0.022	1.205	32.0	1288
161	247.8	0.014	0.021	1.297	31.5	1312
162	250.2	0.014	0.021	1.314	31.8	1312
163	250.2	0.014	0.021	1.307	31.7	1312
164	188.1	0.046	0.069	0.431	90.1	1212
165	188.7	0.033	0.051	0.578	71.2	1049
166	189.3	0.018	0.027	1.024	36.4	1143
167	189.3	0.045	0.062	0.460	70.4	1073
168	182.8	0.047	0.056	0.473	34.1	1026
169	189.3	0.046	0.047	0.518	0.0	1078
170	188.1	0.032	0.055	0.569	93.4	1113
171	189.9	0.033	0.041	0.646	34.6	1055
172	189.3	0.033	0.034	0.709	0.0	1108
173	193.5	0.018	0.034	0.920	68.4	962
174	193.9	0.018	0.019	1.213	0.0	1113
175	187.9	0.002	0.026	2.178	93.5	1656
176	189.1	0.003	0.020	2.305	68.4	1767
177	190.5	0.002	0.011	3.755	32.8	2187
178	189.3	0.048	0.072	0.415	98.8	1271
179	186.9	0.047	0.069	0.427	90.4	1218
180	186.9	0.046	0.068	0.434	89.3	1195
181	189.3	0.035	0.052	0.561	71.4	1049
182	190.9	0.034	0.051	0.573	72.1	1055
183	189.3	0.034	0.052	0.571	72.0	1055
184	189.3	0.018	0.027	1.026	36.1	1136
185	189.3	0.010	0.027	1.320	36.2	1119
186	186.9	0.018	0.028	1.015	36.0	1119
187	127.8	0.064	0.098	0.307	96.8	892
188	127.1	0.042	0.067	0.451	70.9	798
189	125.9	0.018	0.030	0.980	33.7	1189
190	125.3	0.023	0.036	0.794	34.0	1007
191	124.2	0.063	0.088	0.326	65.9	833
192	120.9	0.063	0.075	0.353	31.1	792
193	126.5	0.063	0.064	0.384	0.0	845
194	128.2	0.040	0.072	0.442	87.8	816
195	125.2	0.040	0.052	0.521	30.3	886
196	125.9	0.042	0.042	0.569	0.0	985
197	125.9	0.020	0.052	0.701	89.2	891
198	127.1	0.019	0.043	0.785	64.4	927
199	127.7	0.020	0.021	1.110	0.0	1119
200	125.7	0.020	0.032	0.900	33.7	1096

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 67.5°

S.NO.	G	X_i	X_o	$X_{tt,av}$	a/A	TPD
201	125.9	0.022	0.035	0.830	33.9	1073

PRESSURE DROP DATA ANGLE OF INCLINATION = 46.0°

S.NO.	G	X_i	X_o	$X_{tt,av}$	q/A	TPD
1	769.1	0.004	0.007	4.283	30.9	2824
2	761.5	0.005	0.010	3.156	64.0	3209
3	743.2	0.005	0.010	3.024	62.8	3273
4	753.9	0.006	0.014	2.399	100.0	3664
5	746.3	0.007	0.015	2.097	100.0	3967
6	754.0	0.007	0.013	2.262	67.0	3559
7	738.7	0.008	0.012	2.269	31.4	3623
8	769.1	0.003	0.005	5.163	0.0	2725
9	746.3	0.008	0.015	2.038	97.9	3588
10	746.3	0.010	0.011	2.146	0.0	3180
11	764.5	0.003	0.009	3.715	98.6	3122
12	758.4	0.003	0.009	3.835	66.1	2771
13	749.3	0.004	0.007	3.924	31.2	2655
14	753.9	0.004	0.007	4.283	31.0	2824
15	738.7	0.004	0.007	3.827	31.2	2871
16	743.2	0.004	0.007	3.818	31.0	2824
17	743.2	0.006	0.011	2.766	62.7	3250
18	756.9	0.006	0.011	2.791	62.7	3343
19	746.3	0.008	0.015	2.076	98.7	4014
20	753.9	0.007	0.016	2.072	102.5	4259
21	769.1	0.004	0.005	5.017	0.0	2725
22	766.0	0.004	0.006	4.411	0.0	2725
23	746.3	0.005	0.006	3.876	0.0	2704
24	517.9	0.003	0.004	5.561	0.0	2570
25	477.4	0.008	0.012	2.241	31.7	2632
26	529.9	0.011	0.018	1.671	63.5	3226
27	508.9	0.014	0.023	1.294	84.0	3629
28	514.9	0.013	0.021	1.426	63.0	3647
29	533.7	0.013	0.018	1.531	31.1	3454
30	525.4	0.014	0.015	1.624	0.0	3139
31	516.4	0.010	0.019	1.692	88.5	3880
32	513.4	0.011	0.015	1.802	31.7	3454
33	522.4	0.011	0.012	1.976	0.0	3157
34	508.9	0.007	0.016	2.121	89.1	3127
35	507.4	0.007	0.014	2.206	62.1	2917
36	507.4	0.008	0.010	2.526	0.0	2614
37	510.4	0.002	0.011	4.027	88.0	3092
38	522.4	0.002	0.009	4.387	63.2	2801
39	522.4	0.003	0.007	4.880	31.8	2620
40	508.9	0.003	0.004	5.413	0.0	2544
41	522.4	0.003	0.004	5.450	0.0	2573
42	511.9	0.003	0.005	5.087	0.0	2561
43	514.9	0.009	0.013	2.167	31.5	2462
44	514.9	0.009	0.013	2.132	31.3	2433
45	523.9	0.009	0.013	2.175	31.2	2532
46	499.4	0.011	0.018	1.618	62.7	3081
47	514.9	0.011	0.018	1.653	62.3	3180
48	514.9	0.011	0.018	1.615	63.3	3267
49	499.9	0.013	0.023	1.351	86.0	3372
50	520.9	0.013	0.022	1.383	85.5	3617

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 46.0°

S.NO.	G	X_i	X_o	$X_{tt,av}$	q/A	TPD
51	514.9	0.014	0.023	1.314	85.6	3868
52	430.0	0.003	0.005	5.051	0.0	2626
53	370.9	0.003	0.005	5.294	0.0	2538
54	375.0	0.010	0.016	1.777	32.8	2334
55	383.2	0.016	0.024	1.201	61.8	2276
56	370.1	0.022	0.034	0.873	88.0	2491
57	372.6	0.020	0.029	0.997	61.2	2731
58	401.4	0.019	0.024	1.137	31.5	2585
59	391.5	0.020	0.021	1.172	0.0	2089
60	354.6	0.019	0.031	0.974	88.1	2188
61	361.5	0.017	0.022	1.214	31.5	2077
62	375.0	0.017	0.018	1.372	0.0	1955
63	383.2	0.008	0.020	1.753	89.4	2777
64	363.5	0.009	0.018	1.793	62.7	2608
65	395.6	0.008	0.013	2.157	31.6	2596
66	371.7	0.011	0.012	1.948	0.0	2089
67	371.7	0.002	0.014	3.292	88.8	2521
68	380.0	0.002	0.011	4.015	62.0	3016
69	371.7	0.002	0.008	4.522	31.5	2591
70	370.9	0.003	0.004	6.273	0.0	2538
71	384.9	0.003	0.004	6.348	0.0	2550
72	379.1	0.010	0.015	1.809	32.5	2398
73	387.4	0.010	0.015	1.800	32.6	2427
74	379.1	0.011	0.016	1.719	33.0	2558
75	379.2	0.016	0.025	1.174	61.6	2264
76	380.0	0.017	0.026	1.134	63.8	2258
77	383.2	0.017	0.026	1.114	65.5	2340
78	381.6	0.022	0.034	0.892	87.5	2556
79	383.2	0.020	0.032	0.937	88.7	3028
80	376.7	0.021	0.033	0.931	87.8	2981
81	237.0	0.017	0.023	1.178	0.0	1103
82	225.1	0.036	0.050	0.577	64.6	1120
83	266.9	0.025	0.042	0.737	93.2	1226
84	260.9	0.030	0.042	0.685	63.2	1167
85	251.4	0.032	0.038	0.701	31.7	1298
86	249.0	0.032	0.032	0.755	0.0	957
87	263.3	0.022	0.038	0.827	88.3	1220
88	258.5	0.022	0.028	0.945	31.1	1056
89	258.5	0.023	0.023	1.035	0.0	1015
90	258.5	0.011	0.027	1.278	89.3	1295
91	257.3	0.011	0.022	1.432	62.2	1249
92	254.9	0.011	0.012	1.918	0.0	1278
93	243.0	0.016	0.022	1.214	30.8	963
94	258.5	0.016	0.021	1.266	30.9	963
95	243.0	0.016	0.022	1.216	30.8	963
96	260.9	0.023	0.034	0.842	60.0	1231
97	243.0	0.017	0.028	1.076	58.9	1196
98	243.0	0.026	0.044	0.707	90.0	1138
99	257.5	0.026	0.043	0.722	90.2	1173
100	248.9	0.026	0.043	0.709	90.3	1144
101	201.3	0.031	0.045	0.647	63.0	1080
102	125.9	0.054	0.086	0.359	86.7	776

Contd....

PRESSURE DROP DATA　　ANGLE OF INCLINATION = 46.0°

S.NO.	G	x_i	x_o	$X_{tt,av}$	q/A	TPD
103	130.6	0.034	0.056	0.550	63.4	660
104	124.8	0.022	0.034	0.851	32.8	864
105	120.1	0.054	0.078	0.376	61.2	765
106	124.8	0.052	0.065	0.419	32.5	765
107	131.7	0.049	0.049	0.494	0.0	765
108	135.2	0.037	0.068	0.480	90.3	823
109	130.6	0.039	0.050	0.544	31.8	759
110	137.5	0.036	0.036	0.660	0.0	812
111	125.9	0.024	0.057	0.623	89.6	724
112	123.6	0.023	0.046	0.709	61.5	759
113	122.4	0.023	0.026	0.934	0.0	794
114	125.9	0.001	0.033	2.622	87.6	1126
115	125.9	0.001	0.023	3.280	61.2	1185
116	125.9	0.000	0.012	5.362	31.1	1383
117	125.9	0.051	0.083	0.373	88.5	735
118	128.2	0.049	0.080	0.387	87.6	724
119	122.4	0.051	0.083	0.374	86.6	700
120	116.7	0.037	0.061	0.502	61.3	595
121	125.9	0.035	0.058	0.528	63.1	700
122	125.9	0.036	0.060	0.513	63.5	700
123	128.2	0.022	0.035	0.836	33.4	852
124	128.2	0.022	0.035	0.831	33.3	811
125	121.2	0.025	0.037	0.760	31.4	811
126	125.9	0.009	0.010	2.212	0.0	1167

PRESSURE DROP DATA   ANGLE OF INCLINATION = 30,5°

S.NO.	G	X_1	X_o	$X_{tt,av}$	q/A	TPD
1	761.5	0.002	0.005	5.795	32.0	2120
2	738.7	0.004	0.009	3.359	60.8	2765
3	746.3	0.007	0.014	2.273	87.9	3290
4	712.1	0.008	0.013	2.167	62.0	3243
5	719.7	0.008	0.012	2.315	31.5	3272
6	761.5	0.007	0.008	2.885	0.0	2350
7	749.3	0.002	0.009	4.411	87.7	2829
8	770.6	0.004	0.006	4.358	31.9	2123
9	765.3	0.004	0.005	4.290	0.0	2111
10	765.3	0.001	0.004	8.760	42.2	2076
11	776.7	0.002	0.003	7.131	0.0	2111
12	776.7	0.000	0.001	31.610	0.0	2100
13	753.9	0.001	0.002	14.317	0.0	2100
14	761.5	0.001	0.002	17.996	0.0	2100
15	738.7	0.003	0.006	5.277	31.7	2164
16	738.7	0.003	0.006	4.831	31.3	2129
17	738.7	0.004	0.009	3.347	58.9	2701
18	731.7	0.004	0.009	3.439	57.3	2671
19	746.3	0.005	0.010	3.101	55.8	2747
20	727.3	0.008	0.015	2.114	85.5	3535
21	734.9	0.008	0.014	2.154	84.9	3523
22	727.3	0.008	0.015	2.139	86.6	3541
23	765.3	0.001	0.006	7.534	63.9	2409
24	477.4	0.001	0.002	12.713	0.0	1919
25	522.4	0.009	0.018	1.755	85.6	2747
26	522.4	0.006	0.013	2.341	65.5	2438
27	507.4	0.002	0.006	5.523	32.2	1989
28	477.4	0.010	0.018	1.690	64.6	2572
29	507.4	0.010	0.014	1.983	31.2	2543
30	507.4	0.010	0.011	2.124	0.0	2310
31	492.4	0.006	0.015	2.294	84.6	2473
32	504.4	0.008	0.012	2.215	32.4	2245
33	526.9	0.008	0.009	2.748	0.0	2041
34	529.9	0.003	0.012	3.271	99.0	2496
35	526.2	0.002	0.009	4.391	65.4	2269
36	525.4	0.004	0.005	4.662	0.0	1954
37	526.9	0.001	0.002	16.715	0.0	1930
38	529.9	0.001	0.002	17.123	0.0	1930
39	522.4	0.009	0.018	1.719	87.8	2806
40	522.4	0.010	0.019	1.675	88.0	2837
41	507.4	0.010	0.019	1.642	81.4	2555
42	510.4	0.008	0.015	2.028	68.3	2555
43	522.4	0.008	0.015	2.030	67.8	2625
44	507.4	0.007	0.015	2.124	64.7	2555
45	533.7	0.003	0.007	4.464	31.3	2035
46	514.9	0.004	0.008	3.737	30.3	2024
47	514.9	0.004	0.008	3.920	31.0	2053
48	377.5	0.017	0.028	1.081	83.8	2117
49	391.5	0.016	0.027	1.118	83.6	2170
50	383.2	0.014	0.023	1.290	65.8	2181

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 30.5°

S.NO.	G	X_i	X_o	$X_{tt,av}$	a/A	TPD
51	391.5	0.007	0.012	2.446	32.4	2000
52	362.7	0.018	0.027	1.083	63.1	2000
53	377.5	0.017	0.022	1.207	31.8	1930
54	383.2	0.018	0.019	1.287	0.0	1767
55	381.6	0.010	0.021	1.570	85.0	2164
56	362.7	0.011	0.016	1.721	30.4	1995
57	387.4	0.010	0.011	2.089	0.0	1890
58	358.6	0.006	0.018	1.987	87.4	2152
59	362.7	0.008	0.017	1.900	62.1	2094
60	395.6	0.005	0.006	3.892	0.0	1872
61	377.5	0.019	0.030	0.995	88.4	2216
62	403.0	0.017	0.028	1.081	87.5	2245
63	389.0	0.014	0.023	1.271	66.3	2240
64	387.4	0.015	0.024	1.230	67.1	2234
65	384.1	0.014	0.024	1.254	67.8	2245
66	387.4	0.007	0.011	2.463	31.2	1983
67	387.4	0.006	0.011	2.612	30.2	1954
68	387.4	0.007	0.011	2.496	31.0	1954
69	268.1	0.023	0.038	0.804	85.9	1125
70	251.4	0.016	0.028	1.067	62.3	1131
71	260.9	0.006	0.012	2.416	30.1	1248
72	246.5	0.035	0.047	0.602	65.7	1125
73	270.5	0.030	0.036	0.730	32.2	1050
74	266.9	0.026	0.027	0.889	0.0	910
75	262.1	0.017	0.033	0.964	89.1	1108
76	254.9	0.020	0.026	1.009	31.5	950
77	260.9	0.019	0.019	1.219	0.0	886
78	250.8	0.009	0.024	1.458	81.2	1225
79	232.3	0.011	0.023	1.408	61.2	1073
80	269.3	0.001	0.017	3.904	89.1	1376
81	266.9	0.001	0.013	4.381	64.7	1376
82	266.9	0.001	0.007	7.478	32.0	1493
83	252.6	0.035	0.053	0.569	95.1	1306
84	254.9	0.023	0.039	0.787	82.5	1102
85	254.9	0.023	0.038	0.792	79.5	1073
86	262.1	0.022	0.036	0.841	80.5	1050
87	264.5	0.015	0.027	1.127	63.2	1179
88	263.2	0.014	0.025	1.214	60.9	1195
89	256.1	0.006	0.012	2.392	29.3	1248
90	256.1	0.006	0.012	2.563	29.2	1236
91	269.3	0.011	0.017	1.640	32.0	1085
92	186.9	0.033	0.053	0.578	83.0	939
93	191.7	0.024	0.039	0.773	64.1	892
94	198.9	0.015	0.022	1.266	30.6	875
95	191.7	0.033	0.048	0.601	63.2	892
96	191.7	0.035	0.043	0.620	33.4	810
97	191.7	0.035	0.035	0.681	0.0	769
98	195.3	0.026	0.046	0.685	86.4	927
99	192.9	0.026	0.034	0.791	31.6	816
100	182.9	0.026	0.027	0.889	0.0	781
101	191.7	0.014	0.034	1.035	85.3	904
102	191.7	0.014	0.029	1.116	64.2	830

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 30.5°

S.NO.	G	x_i	x_o	$X_{tt,av}$	a/A	TPD
103	191.7	0.014	0.014	1.610	0.0	746
104	186.9	0.035	0.056	0.540	84.0	892
105	191.7	0.035	0.055	0.550	83.8	980
106	197.7	0.033	0.053	0.573	83.4	980
107	195.3	0.023	0.038	0.790	64.1	892
108	184.5	0.024	0.041	0.748	64.6	857
109	195.3	0.024	0.040	0.761	67.1	892
110	194.1	0.015	0.023	1.236	30.9	834
111	203.6	0.014	0.021	1.325	31.2	880
112	182.2	0.010	0.018	1.607	30.9	834
113	134.0	0.046	0.074	0.418	82.3	781
114	134.0	0.040	0.070	0.456	88.4	769
115	132.3	0.036	0.057	0.531	59.8	635
116	132.9	0.017	0.027	1.077	27.7	635
117	130.6	0.048	0.071	0.417	64.2	699
118	129.4	0.047	0.058	0.467	29.9	612
119	125.9	0.048	0.049	0.501	0.0	606
120	123.6	0.033	0.066	0.508	87.4	746
121	129.4	0.039	0.050	0.546	31.1	548
122	128.2	0.042	0.042	0.572	0.0	653
123	127.1	0.022	0.053	0.674	84.8	763
124	127.1	0.022	0.045	0.739	63.3	519
125	130.6	0.034	0.062	0.520	80.9	764
126	134.0	0.033	0.063	0.520	84.9	775
127	135.2	0.027	0.047	0.663	58.9	729
128	132.9	0.023	0.044	0.735	59.1	740
129	134.0	0.022	0.042	0.769	59.3	775
130	130.6	0.018	0.028	1.007	28.1	676
131	128.2	0.018	0.028	1.014	28.2	647
132	127.1	0.018	0.029	0.992	28.3	740
133	127.1	0.000	0.001	25.052	0.0	1720

PRESSURE DROP DATA ANGLE OF INCLINATION = 00.0°

S.NO.	G	X_1	X_o	$X_{tt,av}$	a/A	TPD
1	741.7	0.005	0.011	3.121	77.8	2602
2	758.4	0.003	0.008	4.026	62.5	1621
3	747.8	0.003	0.006	4.909	34.1	1345
4	749.3	0.003	0.006	4.536	34.6	1370
5	749.3	0.001	0.001	19.453	0.0	513
6	749.2	0.005	0.010	3.039	60.8	2526
7	747.8	0.006	0.009	3.188	0.0	2386
8	735.6	0.006	0.007	3.466	0.0	2211
9	747.8	0.002	0.008	4.427	86.3	1663
10	738.7	0.003	0.006	4.652	30.3	1482
11	740.3	0.005	0.005	4.410	0.0	1295
12	746.3	0.001	0.005	9.578	59.1	764
13	753.9	0.001	0.002	12.343	0.0	391
14	760.0	0.004	0.010	3.213	79.9	2211
15	760.0	0.005	0.011	3.092	80.1	2450
16	753.9	0.005	0.012	2.702	86.6	3378
17	758.4	0.002	0.007	5.087	62.3	1388
18	758.4	0.002	0.007	5.391	61.8	1523
19	753.9	0.005	0.010	3.251	65.4	2695
20	749.3	0.002	0.004	7.802	31.4	776
21	747.8	0.003	0.006	4.516	34.1	1493
22	761.5	0.001	0.002	12.457	0.0	385
23	752.4	0.002	0.002	9.725	0.0	805
24	758.4	0.002	0.002	9.675	0.0	928
25	522.4	0.012	0.022	1.438	91.1	2607
26	520.9	0.009	0.016	1.894	65.7	2404
27	523.9	0.006	0.009	3.054	31.6	1324
28	528.4	0.001	0.002	11.804	0.0	630
29	520.9	0.011	0.018	1.613	64.6	2923
30	520.9	0.012	0.016	1.738	31.3	2351
31	520.9	0.013	0.014	1.782	0.0	1972
32	517.9	0.007	0.016	2.028	88.6	2369
33	507.4	0.011	0.012	1.989	0.0	1598
34	504.4	0.005	0.015	2.491	93.6	1937
35	505.9	0.005	0.012	2.702	67.6	1558
36	504.4	0.006	0.007	3.250	0.0	1108
37	513.4	0.012	0.021	1.460	86.5	2380
38	522.4	0.012	0.021	1.461	89.7	2707
39	517.9	0.010	0.017	1.791	64.8	2479
40	517.9	0.010	0.017	1.766	64.9	2573
41	519.4	0.010	0.017	1.808	64.7	2608
42	522.4	0.005	0.009	3.095	31.7	1768
43	520.9	0.006	0.010	2.856	31.6	1954
44	516.4	0.006	0.009	3.069	31.1	1208
45	522.4	0.001	0.001	15.481	0.0	427
46	519.4	0.001	0.001	17.054	0.0	507
47	522.4	0.001	0.002	13.203	0.0	613
48	371.7	0.017	0.028	1.073	83.4	1516
49	373.4	0.013	0.021	1.416	62.3	1476
50	373.4	0.006	0.011	2.666	30.7	893

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 00.0°

S.NO.	G	x_i	x_o	$X_{tt,av}$	a/A	TPD
51	375.0	0.001	0.002	12.476	0.0	648
52	380.0	0.019	0.027	1.073	59.9	1313
53	371.7	0.016	0.020	1.314	29.9	1219
54	373.4	0.016	0.017	1.404	0.0	1120
55	371.7	0.011	0.022	1.440	83.7	1423
56	373.4	0.012	0.016	1.642	29.9	1190
57	373.4	0.013	0.013	1.791	0.0	1079
58	368.5	0.005	0.015	2.363	79.3	1038
59	371.8	0.006	0.014	2.295	60.6	893
60	376.7	0.007	0.008	2.890	0.0	782
61	376.7	0.018	0.029	1.043	84.7	1248
62	370.1	0.017	0.028	1.098	82.7	1412
63	376.7	0.014	0.022	1.352	63.6	1552
64	375.0	0.014	0.023	1.308	64.0	1598
65	371.7	0.014	0.022	1.344	64.0	1598
66	376.7	0.007	0.011	2.510	31.2	939
67	378.3	0.007	0.012	2.421	31.5	863
68	375.0	0.007	0.011	2.520	30.6	805
69	373.4	0.001	0.002	12.820	0.0	362
70	252.6	0.025	0.042	0.745	89.5	758
71	244.2	0.018	0.030	0.997	61.2	630
72	246.6	0.008	0.014	2.042	33.3	432
73	246.0	0.025	0.039	0.769	69.9	677
74	245.4	0.026	0.032	0.840	32.0	560
75	243.0	0.026	0.026	0.915	0.0	455
76	244.2	0.019	0.036	0.914	90.4	712
77	243.6	0.019	0.026	1.058	32.4	519
78	241.2	0.019	0.019	1.223	0.0	432
79	243.0	0.010	0.028	1.335	91.7	677
80	244.2	0.010	0.023	1.456	66.9	554
81	244.2	0.011	0.011	2.022	0.0	333
82	246.6	0.026	0.043	0.717	88.0	753
83	247.8	0.025	0.042	0.745	88.3	735
84	248.4	0.025	0.041	0.751	88.8	776
85	246.6	0.018	0.030	1.027	62.0	630
86	248.4	0.019	0.031	0.985	63.0	648
87	247.8	0.019	0.031	0.978	64.1	659
88	245.4	0.009	0.016	1.820	33.5	443
89	249.0	0.010	0.008	2.484	33.5	385
90	247.8	0.010	0.017	1.717	33.5	385
91	185.4	0.033	0.056	0.564	90.9	583
92	179.2	0.027	0.044	0.695	66.2	449
93	195.3	0.014	0.022	1.326	33.8	309
94	178.6	0.044	0.061	0.475	65.3	572
95	180.4	0.045	0.053	0.508	33.2	443
96	178.6	0.046	0.046	0.536	0.0	367
97	179.2	0.030	0.053	0.608	88.2	618
98	178.0	0.030	0.039	0.706	32.0	356
99	177.5	0.030	0.031	0.789	0.0	286
100	186.9	0.013	0.035	1.044	87.7	518
101	187.5	0.014	0.030	1.119	65.4	397
102	183.4	0.013	0.014	1.667	0.0	198

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 00.0°

S.NO.	G	X_i	X_o	$X_{tt,av}$	q/A	TPD
103	183.8	0.036	0.058	0.536	91.4	583
104	181.6	0.036	0.059	0.532	89.9	583
105	180.4	0.036	0.058	0.535	89.7	583
106	178.6	0.028	0.045	0.682	66.2	437
107	167.6	0.029	0.047	0.646	65.6	414
108	168.2	0.029	0.047	0.648	66.2	414
109	193.5	0.013	0.021	1.398	32.7	274
110	198.3	0.014	0.022	1.290	33.9	321
111	195.3	0.014	0.022	1.298	33.5	297
112	128.2	0.056	0.086	0.357	83.5	437
113	130.0	0.036	0.059	0.526	65.8	327
114	123.6	0.014	0.026	1.188	32.0	163
115	125.3	0.066	0.091	0.321	68.2	484
116	125.3	0.065	0.077	0.353	32.7	362
117	125.3	0.063	0.064	0.392	0.0	320
118	124.5	0.044	0.077	0.421	90.4	484
119	124.8	0.043	0.055	0.502	31.2	239
120	124.8	0.042	0.042	0.575	0.0	175
121	121.9	0.013	0.044	0.932	82.5	315
122	126.5	0.012	0.035	1.055	63.6	251
123	125.9	0.014	0.014	1.632	0.0	163
124	128.2	0.055	0.085	0.361	83.1	426
125	130.6	0.055	0.085	0.361	84.3	437
126	128.8	0.054	0.083	0.368	81.7	437
127	129.4	0.037	0.060	0.519	66.0	315
128	130.0	0.036	0.059	0.525	65.2	315
129	130.6	0.036	0.058	0.531	65.1	315
130	126.5	0.013	0.025	1.242	31.7	152
131	126.5	0.014	0.025	1.225	31.5	152
132	126.5	0.014	0.025	1.223	31.4	163
133	124.8	0.000	0.000	86.853	0.0	70
134	127.1	0.001	0.001	22.794	0.0	58
135	105.1	0.077	0.115	0.263	87.5	583
136	103.9	0.052	0.081	0.380	64.9	414
137	104.5	0.020	0.033	0.908	29.5	140
138	103.9	0.002	0.002	8.774	0.0	58
139	108.3	0.067	0.094	0.313	64.9	391
140	107.0	0.068	0.082	0.333	32.4	280
141	107.2	0.068	0.068	0.366	0.0	210
142	107.4	0.049	0.085	0.382	85.7	449
143	107.4	0.049	0.064	0.440	33.5	257
144	107.4	0.049	0.050	0.496	0.0	157
145	107.4	0.021	0.058	0.653	87.5	362
146	106.2	0.021	0.048	0.728	64.0	292
147	107.4	0.021	0.021	1.096	0.0	145
148	107.4	0.001	0.037	2.044	84.5	268
149	107.4	0.001	0.028	2.804	63.7	233
150	107.4	0.000	0.013	5.314	29.2	140

Contd....

PRESSURE DROP DATA ANGLE OF INCLINATION = 00.0^{o}

S.NO.	G	X_i	X_o	$X_{tt,av}$	α/A	TPD
151	104.5	0.077	0.115	0.264	85.9	624
152	103.3	0.077	0.114	0.266	84.6	601
153	103.9	0.079	0.117	0.260	87.0	624
154	103.9	0.052	0.080	0.384	63.9	449
155	103.9	0.051	0.080	0.385	64.1	397
156	103.9	0.053	0.082	0.374	64.6	379
157	104.5	0.021	0.033	0.888	29.4	146
158	104.5	0.023	0.036	0.829	29.5	146
159	102.8	0.023	0.036	0.809	28.8	146
160	102.8	0.002	0.002	8.486	0.0	58
161	102.8	0.002	0.002	9.120	0.0	58
162	103.3	0.002	0.002	9.817	0.0	58

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